Vulnerabilities to Seismic Hazards in Coastal and River Environments:

Lessons post the

Canterbury Earthquake Sequence 2010-2012, New Zealand

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ABSTRACT

Coastal and river environments are exposed to a number of natural hazards that have the potential to negatively affect both human and natural environments. The purpose of this research is to explain that significant vulnerabilities to seismic hazards exist within coastal and river environments and that coasts and rivers, past and present, have played as significant a role as seismic, engineering or socio-economic factors in determining the impacts and recovery patterns of a city following a seismic hazard event. An interdisciplinary approach was used to investigate the vulnerability of coastal and river areas in the city of Christchurch, New Zealand, following the Canterbury Earthquake Sequence, which began on the 4th of September 2010. This information was used to identify the characteristics of coasts and rivers that make them more susceptible to earthquake induced hazards including liquefaction, lateral spreading, flooding, landslides and rock falls. The findings of this research are applicable to similar coastal and river environments elsewhere in the world where seismic hazards are also of significant concern.

An interdisciplinary approach was used to document and analyse the coastal and river related effects of the Canterbury earthquake sequence on Christchurch city in order to derive transferable lessons that can be used to design less vulnerable urban communities and help to predict seismic vulnerabilities in other New Zealand and international urban coastal and river environments for the future. Methods used to document past and present features and earthquake impacts on coasts and rivers in Christchurch included using maps derived from Geographical Information Systems (GIS), photographs, analysis of interviews from coastal, river and engineering experts, and analysis of secondary data on seismicity, liquefaction potential, geology, and planning statutes.

The Canterbury earthquake sequence had a significant effect on Christchurch, particularly around rivers and the coast. This was due to the susceptibility of rivers to lateral spreading and the susceptibility of the eastern Christchurch and estuarine environments to liquefaction. The collapse of river banks and the extensive cracking, tilting and subsidence that accompanied liquefaction, lateral spreading and rock falls caused damage to homes, roads, bridges and lifelines. This consequently blocked transportation routes, interrupted electricity and water lines, and damaged structures built in their path.

This study found that there are a number of physical features of coastal and river environments from the past and the present that have induced vulnerabilities to earthquake hazards. The types of sediments found beneath eastern Christchurch are unconsolidated fine sands, silts, peats and gravels. Together with the high water tables located beneath the city, these deposits made the area particularly susceptible to liquefaction and liquefaction-induced lateral spreading, when an earthquake of sufficient size shook the ground. It was both past and present coastal and river processes that deposited the types of sediments that are easily liquefied during an earthquake. Eastern Christchurch was once a coastal and marine environment 6000 years ago when the shoreline reached about 6 km inland of its present day location, which deposited fine sand and silts over this area. The region was also exposed to large braided rivers and smaller spring fed rivers, both of which have laid down further fine sediments over the following thousands of years.

A significant finding of this study is the recognition that the Canterbury earthquake sequence has exacerbated existing coastal and river hazards and that assessments and monitoring of these changes will be an important component of Christchurch's future resilience to natural hazards. In addition, patterns of recovery following the Canterbury earthquakes are highlighted to show that coasts and rivers are again vulnerable to earthquakes through their ability to recovery. This city's capacity to incorporate resilience into the recovery efforts is also highlighted in this study.

Coastal and river areas have underlying physical characteristics that make them increasingly vulnerable to the effects of earthquake hazards, which have not typically been perceived as a 'coastal' or 'river' hazard. These findings enhance scientific and management understanding of the effects that earthquakes can have on coastal and river environments, an area of research that has had modest consideration to date. This understanding is important from a coastal and river hazard management perspective as concerns for increased human development around coastlines and river margins, with a high seismic risk, continue to grow.

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1 CHAPTER ONE: INTRODUCTION

1.1 Thesis Statement

Coastal and river environments are exposed to a number of natural hazards, which have the potential to negatively impact both human and natural environments. This is particularly true for the country of New Zealand, which is a strongly coastal nation, both in a physical sense with a coastline stretching 19,883km (Collins and Kearns, 2008) and also in a human sense, as five of the six largest cities are located by the coast. In New Zealand 65% of the population live within 5 km of the coast and 75% live within 10km of the coast (Statistics New Zealand, 2006). Subsequently, the beach features prominently in New Zealand's national identity. New Zealand is also strongly dominated by river environments with prominent rivers and streams incising a majority of the country at almost every turn and rivers total a combined length of around 180,000 km (Young, 2009). Residing near the coastline or near river banks is perceived as the two most favourable areas to live in within New Zealand and property prices are usually highest around coastal and riverside areas.

Data from the Real Estate Institute of New Zealand revealed that in the five year period ending May 2006, national medium house prices increased by 74% and an examination of six small coastal towns during the same time period saw property prices increased between 125% and 240% (Collins and Kearns, 2008). These pose significant issues to property owners and developers within these environments as they will at some point experience and have to cope with the effects of naturally occurring coastal and river hazards. As such, it is important to comprehensively recognise the natural hazards that operate within coastal and river environments and understand the extent to which an area is vulnerable to their effects. This understanding assists in effectively manage the risk of natural hazards, especially when there is growing concern about the continual increase and intensification of development along coastlines and river areas.

Earlier studies within the field of hazard management have researched how natural hazards have impacted upon human communities and how communities in different environments can be more vulnerable to the effects of hazards. In coastal and river regions, generally studies have been specifically on hazards including but not limited to floods, erosion, storm surge and the cumulative effects of sea level rise. More recently, the coastal and river city of Christchurch, New Zealand has shown us that coastal and river areas have underlying physical characteristics that make them increasingly vulnerable to the effects of earthquakes, which have not typically been perceived as a ‘coastal’ or ‘river’ hazard. Typical coastal hazards as described in the New Zealand Coastal Policy Statement include sea level rise, coastal erosion or accretion, coastal inundation, storm surge and Tsunami, while river hazards primarily consist of river channel flooding and the potential for river avulsion (channel movement), all of which have the potential to negatively impact human developments.

Arthurton (1998) considers a range of natural hazards that affects coastal cities including tropical cyclones, which exhibit hazards consisting of high rain fall and severe winds and notes that low lying coastal areas are prone to wave erosion and marine inundation caused by associated storm surges. This demonstrates that coastal areas are particularly vulnerable to a wide variety of hazards extenuating from their proximity to large water bodies and maritime climates. The natural hazards that have not been typically perceived as coastal or river hazards include volcanoes, lahars, geothermal hazards and seismic hazards. This fact alone demonstrates that there is a gap in coastal and river hazard research, where the vulnerability of these environments to these types of hazards has not been thoroughly investigated.

The Canterbury earthquake sequence began on the 4th September 2010 where the region was struck by a 7.1 Mw (moment magnitude) earthquake. Five months later on the 22nd of February 2011 the region was again struck by another earthquake of magnitude 6.3. The sequence then continued with another 6.3 magnitude earthquake on the 13th June 2011 and two more earthquakes followed on the 23rd of December consisting of a 5.3 and 5.8 magnitude tremor. These earthquakes have highlighted that coasts and rivers, past and present have played as significant a role as seismic and engineering or socio-economic factors in determining the impacts and recovery of a city, following a seismic hazard event.

The purpose of this research is to explain that significant vulnerabilities to seismic hazards exist within coastal and river environments and not just vulnerabilities to general ‘coastal and river hazards’. This research will provide an understanding of how coasts and rivers, past and present, have induced natural vulnerabilities to earthquakes and associated earthquake induced hazards. A multidisciplinary approach will be used to document and analyse the coastal and river related effects of the Canterbury earthquakes on Christchurch city in order to derive transferable lessons that can be used to design less vulnerable urban communities and predict vulnerabilities in other New Zealand and global urban coastal and river environments. Methods to be employed include the use of maps derived from Geographical Information Systems (GIS), photographs, together with the analysis of interviews from coastal, river and engineering experts and analysis of secondary data on seismicity, liquefaction potential, geology, and planning statutes. This information can be used to help observe vulnerabilities in other coastal and river cities in New Zealand and help derive new development and management strategies that may decrease vulnerability of coastal and riverside environments towards the impacts of seismic hazards.

This chapter introduces the conceptual framework of this research in terms of national and international literature on coastal and river environments, natural hazards, and the increasingly popular terms of vulnerability and resilience. Gaps in existing research on coastal hazards are highlighted. This is then followed by the definition of specific research objectives and lastly, a synopsis of the structure of this thesis and the contents within the individual chapters are presented.

1.2 Conceptual Framework

Coastal and river environments are complex, dynamic and are increasingly developed for human occupancy as they are perceived as desirable environments to live in. Communities that reside in coastal or riverside environments are vulnerable to the impacts of naturally occurring physical processes, which pose a hazard to the built human environment. Because of human development and occupancy of these areas, robust knowledge and management of these environments is essential to enable communities to cope with and recover from the impacts of natural hazards. This project employs a multidisciplinary methodological framework to document, analyse and understand the vulnerability of coastal and river environments to seismic hazards, which have not typically been perceived as a coastal or river hazard and subsequently, have been under-researched in previous literature. The Canterbury earthquake sequence is a case study that will be used in this research to provide the information required to analyse the vulnerability of coastal and river environments to seismic hazards. The methodological techniques employed by this project to achieve this include the use of photographs, interviews of coastal and river experts and the use of Geographical Information Systems (GIS) for the production of visual maps.

Coastal and river environments and their related hazards have been subject to increasing amounts of research over the past few decades. Development of these areas has intensified and subsequently so too has the need for more robust knowledge of the many natural hazards that threaten these areas. The concepts of vulnerability and resilience are terms that have received increased recognition in the field of natural hazard management and these concepts will be discussed later in this chapter. They are important terms as they provide reasoning for why there are variations in the intensity of effects between areas impacted by the same natural event.

1.2.1 Urban Development in Coastal and River Environments

Coastal and river cities are likely to be aware of the hazards that they are at risk from because of their maritime or river location but potentially less aware of the hazards that are not typical for their location, mainly because the hazard may not have occurred previously (Arthurton, 1998). There is potentially less awareness by some coastal and river inhabitants of the vulnerability of these areas to hazards associated with earthquakes, except maybe tsunami, especially in an area not previously known to experience earthquakes but where the risk of an earthquake is still present. This is a huge cause of concern in terms of continuing development and increase in population growth within coastal and river environments, particularly in areas where there is known active fault lines.

Urban development surrounding coastal and river environments has dramatically increased and intensified over the last 100 years (Kullenberg, 2001). Coastal and river cities have grown from historic port and barge developments and while port functions remain a focus of economic activity, most coastal cities have grown far beyond their port's original locations (Arthurton, 1998). It is estimated that 23% of the world's population live within 100 km of the coastline and by the year 2030 it is estimated that 50% of this population will occupy a coastal zone (Gulieria and Patterson Edward, 2012; Li, 2003;). Urbanisation is a major driver of changes to the earth's physical surface as well as to changing natural geomorphological processes. Urban populations have increased by 100% in the third quarter of the twentieth century alone, which represents a large number of people now residing in urban areas surrounding coast lines, river mouths and within river banks and flood plains (Chin, 2006).

One of the outstanding characteristics of this rapid urbanisation is the migration of populations towards rivers and coastlines, which has resulted in the formation of coastal mega-cities with populations of well over 1 million. In 2001 there were 27 coastal megacities with populations of above 1 million: 12 with 1 to 10 million, 13 with 10 to 20 million and two above 20 million. The forecast for 2015 is that there will be 36 coastal megacities with 30 of these in developing countries including 22 in Asia alone (Kullenberg, 2001). With increased population growth there is an increase in infrastructure and reclamation of land from the sea in order to accommodate these growing populations. Any increase in urban development in coastal and river environments ultimately influences natural coastal and river processes and this may, in turn, cause an increase in a city's vulnerability to hazard events in the long or short term.

1.2.2 Natural Hazards and Disasters

This study recognises that there is current debate surrounding the use of the word 'natural' when discussing hazards and disasters, the debate centres on the fact that it is usually aspects of the social and physical environment that contributes to the impacts of hazard events. This is because deaths, injuries and infrastructure damage due to a hazard event can be attributed to inappropriate development, poor building design, poverty, lack of emergency preparedness and many other human associated issues, that are not typically 'natural' issues. For this reason, hazards and disasters should not be considered as 'natural' but considered as an interaction between a human system and a natural event system leading to a disaster.

Geographers have long been interested in natural hazards. Initial research was concerned with the physical processes that drive hazards as well as their temporal and spatial dimensions. Research focussed predominantly on describing natural hazards rather than analysing them and placed the responsibility of hazards purely on nature and not on the human activities that may have induced them (Montz and Tobin, 2011). This is in stark contrast to natural hazard research today, where research includes not only sound understanding of physical natural processes but also in solving societal and human development problems which contribute to natural hazards and disasters. Different definitions of natural hazards have not only evolved over time but they have reflected the approach of studying them by the different disciplines involved (Alcantara-Ayala, 2002).

Defining natural hazards is the first step towards understanding them and there are multiple definitions found in scientific literature concerning natural hazards (Table 1.1). Lazoya *et al* (2011) define natural hazards as a function of a specific natural process and a human activity that may lead to strong negative impacts on society (i.e economic losses, damages, loss of life and injuries) while Alcantara-Ayala, 2002 defines them as the occurrence of a natural condition or phenomenon, which threatens to or acts hazardously in a defined space and time. Gares *et al.* (1994) explain that geomorphic hazards can be regarded as a group of threats to human resources resulting from the instability of the Earth's surface features. Over all, natural hazards are threatening events, capable of producing widespread damage to the physical and social environments where they take place, not only at the moment of the event but over longer time frames. When these hazards have major negative effects on society and the natural and built environment, they become natural disasters. However, natural hazards should be understood as the outcome of a development process whereby human societies have generated their own vulnerabilities and risks and the danger posed by natural hazards is not from the natural process itself but from the interaction of human systems with the natural process and thus creating vulnerability to them (Lozoya *et al.* 2011; Alcantara-Ayala, 2002) (Figure 1.1).

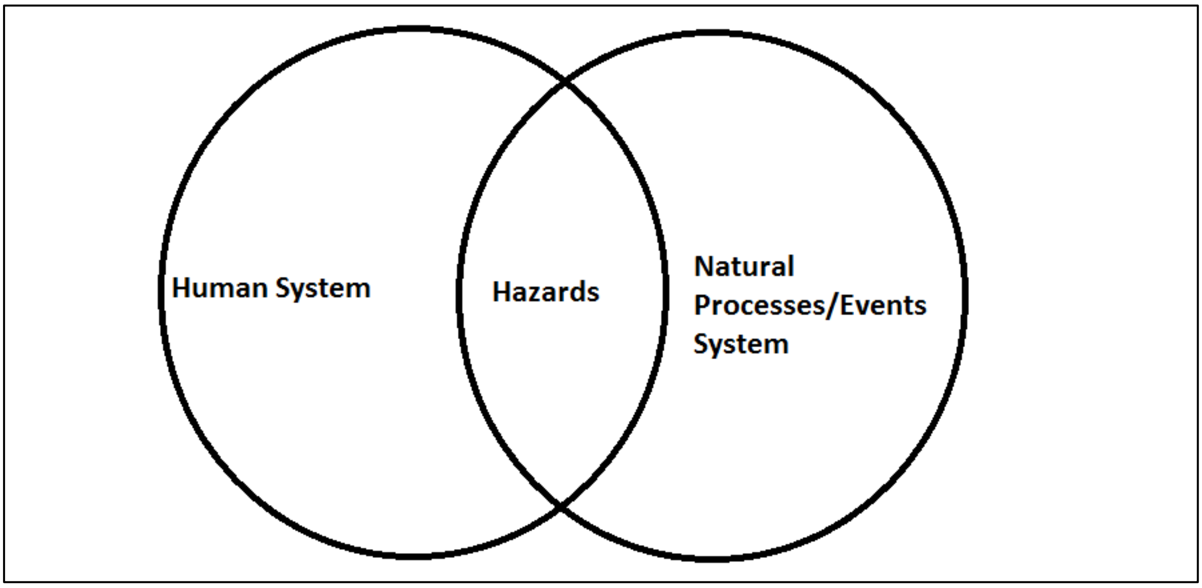


Figure 1.1: Diagram showing how the interaction between the human systems and natural process systems create hazards. Natural events can occur without being a hazard because people are not involved.

Natural disasters only began to occur when human beings began to interact with and change natural environmental processes (Alcantara-Ayala, 2002 and Montz and Tobin, 2011). A natural disaster is defined as a "serious disruption affecting a community or population, causing deaths, injuries, or damage to property, livelihoods or the environment that exceeds the ability of the affected community to cope using its own resources" (Boon *et al.* 2012: 383). In the 1960s natural disasters were understood as uncontrollable events in which society undergoes severe danger and disruption of essential functions of society. Fritz (1961) and Westgate and O'Keefe (1976) defined natural disasters as the interaction between extreme physical or natural phenomena and a vulnerable human group, resulting in potential disruption and destruction, loss of life, livelihood and injury (Fritz, 1961; Westgate and O'Keefe, 1976). Today, billions of people in more than 100 countries are exposed to at least one natural disaster periodically and there are around 30 identified natural disasters worldwide which have the potential to cause devastating impacts on human life, economies and the environment (Seneviratne *et al.* 2010).

An increasing number of natural disaster definitions emphasise extreme (function of magnitude) and rare (function of time) natural phenomena that exceed human abilities to resist (Gaillard *et al.* 2010). This idea can be understood in the context of the fact that before the evolution of Homo sapiens on Earth, all geophysical events including volcanic eruptions, cyclones, earthquakes and tsunamis threatened only living flora and fauna and millions of years later, human presence transformed geophysical events into natural hazards and disasters. This can be illustrated again, due to the fact that natural events can occur today without causing a hazard or a disaster, if the event occurs in an unpopulated area.

Natural disasters stem from earthquakes, tsunamis, floods, tropical storms, famine, drought and epidemics (Boon *et al.* 2012) and trends in the occurrence of natural disasters and the amount of losses they induce have generally increased over the last century (Hewitt, 2007) (Figure1.2). The global toll of natural disasters rises at least as fast as the increase in population and material wealth rises and in developing countries disasters are more frequent and catastrophic (White *et al.* 2001). Population growth, rapid urbanisation and large scale occupation of hazardous areas are among the most visible human causes of the reoccurrence of extreme natural disasters (Nuno Martins *et al.* 2012).

Natural disasters are occurring more frequently and have caused an increase in both human and financial losses (Djalante *et al.* 2012) (Figure 1.2). Trends in natural hazards can be related to land use changes and growing concentration of people and infrastructure in vulnerable areas such as coastal regions, river mouths and flood plains (Hill *et al.* 2012). Hazards occur on different temporal and spatial timescales and differ in their severity, magnitude and in their frequency and predictability. Some natural events take place over a matter of seconds, most notably earthquakes, while others take place over longer time periods, particularly erosion and sea level changes. Some cover large spatial expanses, such as floods, while others cover only small areas such as rock falls (Alcantara-Ayala, 2002).

There are two main types of natural hazards. The first is physical extreme hazard events and the second is physical long-term hazard events. The first may be catastrophic in their impacts while the second may not constitute a direct threat but, has important social and economic implications over a long-term period. In a coastal context, the first type may include severe waves, storm surges, floods, and tsunamis while the second type may include relative seal level changes, coastal erosion and accretion and saline intrusion (Arthurton, 1998).

Table 1.1: Table of natural hazard research definitions

Term	Definition	Example
Natural hazard	A threat of a naturally occurring event that will have a negative effect on people.	Earthquakes, volcanoes, floods, tropical storms, tsunamis, landslides, erosions, avalanches.
Natural disaster	A major event resulting from naturally occurring processes that has negative effects on people.	Indonesian Tsunami 2004 ~230 000 people killed Haiti Earthquake 2010 ~316 000 people killed Hurricane Katrina 2005 ~1836 people killed
Vulnerability	The susceptibility of people or the environment to suffer negative effects in a potentially dangerous event.	
Resilience	The ability of people or the environment to absorb change, learn and adapt after a natural event occurs.	
Recovery	The ability of people or the environment to return to a pre-event level of functioning.	

The trend of coastal and river urban growth is set to continue. The geographic setting of coastal cities has provided opportunities for urban development, but they now and continually impose constraints to sustainable development. Understanding natural hazards and recognising a city's vulnerability towards them are key elements in planning for sustainable development and implementing effective adaptive measures (Arthurton, 1998).

Consequences of natural hazard events may be short term or pose irreversible affects on social, economic and natural structures of the affected region. As such, scientific research and assessments of hazards need to be undertaken in order to understand the processes (both human and natural) that contribute to the potential hazard risk, in order to prevent natural disasters from occurring. Impact assessments are an essential tool which precedes the recovery or rehabilitation program after the occurrence of a natural hazard and the methodology adopted in assessing impacts has implications for mitigation strategies and planning adaptive measures for the impacted city or region (Patwardhan and Sharma, 2005).

As noted above natural hazards differ in their severity and predictability and the ability of managers and planners to set in place effective adaptive measures to cope with significant hazard events depends upon the ability to sufficiently predict the risk and severity of an event. Natural hazards are studied widely in science in order to improve knowledge and understanding of underlying processes that drive hazards and this research contributes to management and planning decisions that strive to reduce the impacts of natural hazards (Arthurton, 1998).

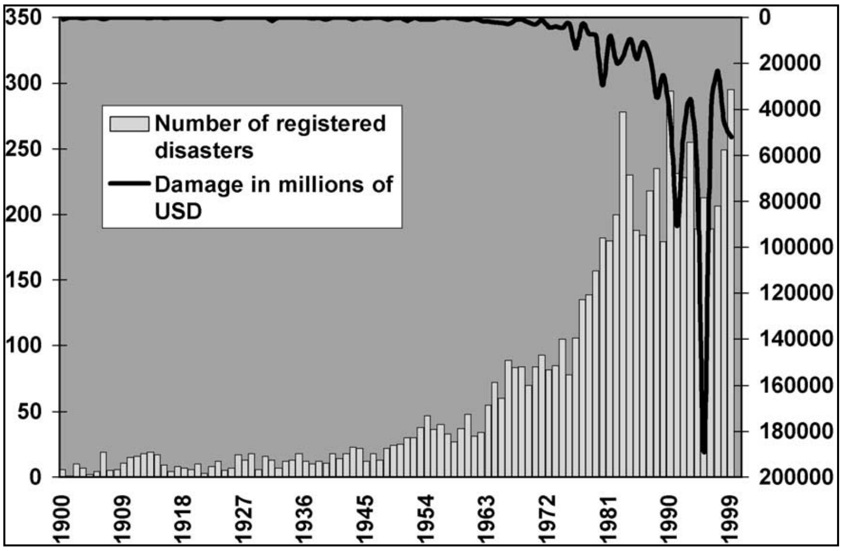


Figure 1.2: Number of disasters and associated damage worldwide between 1900 and 1999 (Source: Alcantara-Ayala, 2002: 110)

1.2.3 Seismic Hazards

There is a wide scope of research into how natural hazards affect coastal and river environment, yet there appears to be little research into how specifically earthquake hazards can significantly impact coastal and river environments. As such the following section will focus upon earthquakes and how they have been studied in recent literature and will also identify areas of research where the link between coastal and river vulnerability to earthquake hazards has been identified.

During the last century, over 1000 significant earthquakes have occurred in around 70 countries across the world, taking the lives of 1.53 million people and causing huge financial losses (Seneviratne, 2010). Earthquakes are a geological process of long term energy accumulation and the abrupt or slow release of energy that causes significant effects on the Earth's natural and anthropogenic surface. Tectonic earthquakes can be divided into two types 1) plate margin earthquakes and 2) intraplate earthquakes. The plate margin earthquakes occur at plate boundaries and are strictly controlled by the motion of plates relating to the rising and falling of the earth's mantle which causes plate boundaries to move against one another. These trigger 98% of the world's earthquakes. Intraplate earthquakes are very rare and occur along faults in the interior of plates and account for less than 2% of earthquakes observed in the world to date. These earthquakes often occur at the location of ancient failed rifts because such old structures may present a weakness in the crust, where it can easily slip to accommodate regional tectonic strain. (Weiran *et al.* 2009). Plate margin earthquakes are significant to coastal areas as many plate boundaries are located along the coastlines.

The built environment is at risk from several secondary hazards directly caused by earthquakes. These hazards comprise of direct ground shaking, tsunami and ground failures which include landslides, liquefaction, and surface fault ruptures (Figure 1.3). All these hazards are a direct result of permanent ground deformation and have the potential to cause significant damage to houses, essential lifelines and infrastructure (Bird and Bomer, 2004).

The estimate of probable future losses as a result of earthquakes is of increasing interest to insurance companies and governments that manage earthquake prone regions. However, there are large uncertainties in the pattern and predictability of earthquakes in time and space and there is also limited understanding of the many vulnerable elements of the built environment that are affected by earthquake hazards. As such, assessment of potential earthquake damage is usually carried out based on statistical and probabilistic techniques (Yucemen *et al.* 2004).

Seismic vulnerability assessments traditionally incorporate a statistical model which yields assessments of the vulnerability of the built environment to seismic hazards. These statistical models usually deal merely with engineering and seismic issues and do not usually include information on the socio-economic or geomorphological components that contribute to vulnerability. For example the statistical model developed by Yucemen *et al* (2004) incorporated data from six earthquakes in the Turkey region from 1992-2002, which in combination caused the loss of around 16,000 lives. The objective of the model was to estimate the seismic vulnerability of low to mid rise reinforced concrete buildings. The model was used to estimate the damage state of buildings ranging from no damage to collapse, with intermediate damage states of light, moderate and severe. Overall correct classification rates ranged from 62% to 95% for the seismic damage data associated with the earthquakes in Turkey (Yucemen *et al.* 2004). A set back of this model was that it did not incorporate geomorphological data, including soil type, water tables, and land forms (coastlines or rivers) or socio-economic data, all of which can contribute towards increasing the risk of effects as a result of earthquake hazards.

The disaster and emergency management of earthquakes occurs through the actions and planning of people, buildings and procedures prior to an event as well as during and post the seismic event phase. Most significantly, studies have focussed on the management of earthquake effects in the post seismic phase which incorporates the emergency response, rescue, recovery and planning of urban cities. Many cities worldwide have developed Earthquake Rapid Response Information (ERRI) which incorporates an output of information on casualties, building and lifeline damages after a significant earthquake. The study by Erdik *et al* (2011) focuses on the use of ERRI systems and how the system potentially reduces the impacts of earthquakes on urban societies by inducing timely and correct action and response taken after an earthquake has occurred.

EERI works by using technology that measures real time ground motion shaking throughout a city and configures areas of intense shaking with areas of intensified building infrastructure and population. This information produces a shake maps showing where response and rescue operations should be a priority.

A reduction in casualties in urban areas could be improved if location and severity of damage can be rapidly assessed with the use of ERRI systems (Erdik *et al.* 2011). As such, the study by Erdik *et al* (2011) focussed on researching the emergency preparedness and responses of cities to earthquake events and argued that having prompt and sufficient emergency plans would significantly reduce urban society’s vulnerability to seismic hazards.

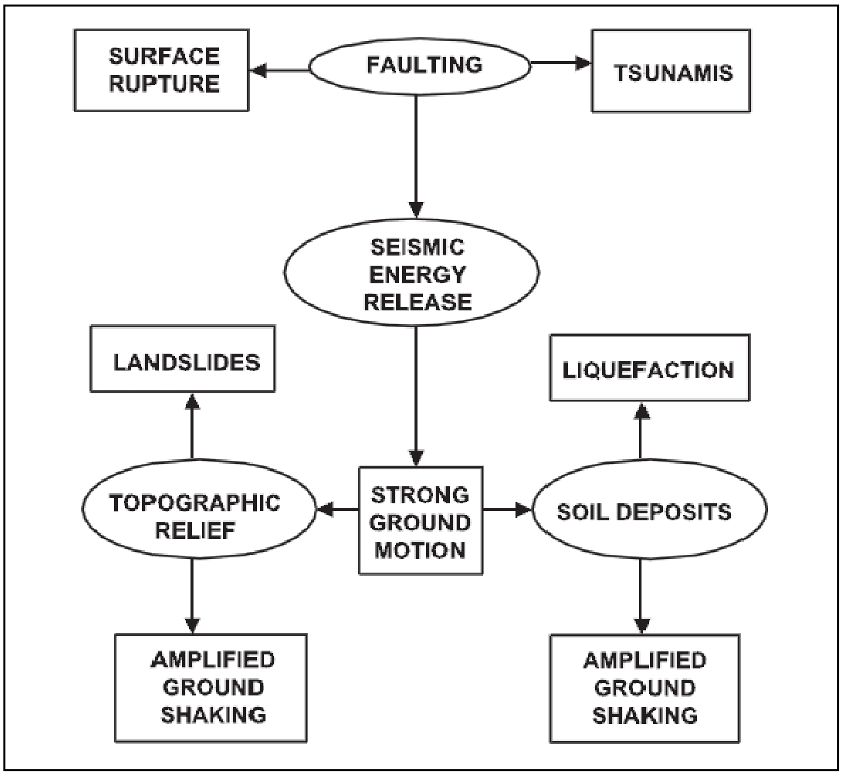


Figure 1.3: Seismic hazards facing the built environment (Source: Bird and Bommer, 2004: 148)

The last decade or so has witnessed a growing interest in assessing vulnerability and associated risks to seismic hazards (Dolce *et al.* 2006). Preparing scenarios of vulnerability to seismic hazards requires contributions from disciplines spanning seismology, geology, geomorphology, geotechnical and structural engineering and economics. For example the paper by Dolce *et al* (2006) compared the prevailing Greek and Italian methodologies for seismic risk assessments in order to construct loss scenarios for the building stock of Potenza City in Southern Italy. They identified similarities and differences in the impacts of past earthquakes using the results of the two assessment methodologies in order to highlight possible improvements in vulnerability assessments. Again, this paper focused on the development of hazard prevention strategies that focus upon adjusting vulnerability through changes in the structural engineering of buildings and infrastructure. But, these changes alone do not take into account information on the natural or social conditons that contribute information for vulnerability assessments.

The study by Bird and Bommer (2004) reviewed 50 earthquakes from 1989-2003 with a magnitude greater than Mw 5.5 in order to establish an inventory of the risks posed by various seismic hazards. They established that the primary cause of earthquake induced damages to buildings was the result of direct ground shaking in 88% of the 50 surveyed events, while 6% of building damage was caused by landslides and the last 6% caused by tsunamis. The secondary cause of building damage in the surveyed earthquakes showed that ground failures rather than ground shaking became more important, with 12% of cases experiencing landslides and 20% experiencing liquefaction. However, for over half the cases there were no secondary cause apart from direct ground shaking.

Earthquakes have a determining influence on slope stability that causes landslides. Both natural and artificial slopes may become equally unstable during earthquakes. The earthquake triggers ground failure landslides, but it is not usually the primary cause, previous weathering, erosion, sedimentation and deforestation reduces the strength of subsurface soils or changes in the geometry of the slope or manmade influences such as road cuts and land use changes are normally the primary cause of failed slopes and landslides during earthquakes (Hack *et al.* 2007).

Bird and Bommer (2004) comprised one of a small number of papers that noted the susceptibility of coastal and river environments to earthquake induced hazards. Their paper noted that 31 of the 50 earthquakes surveyed experienced liquefaction hazards and of these 31 events, 26 occurred in coastal areas. The paper makes clarifications on why liquefaction occurred during these earthquakes, explaining that "*liquefaction frequently occurs in reclaimed soils in coastal areas or poorly compacted man made fill and is also a common occurrence in alluvial or deltaic deposits including old or existing river beds"*(Bird and Bommer, 2004: 159). Arthurton (1998) also recognised earthquakes as a specific coastal hazard and is listed alongside a list of physical extreme events that affect coastal cities including severe waves, storm surge, and tsunamis.

Arthurton (1998) explains that "*coastal lowlands are vulnerable to the marine-related impacts of coastal earthquakes in three ways. They may be affected directly by vertical ground displacement causing possible relative sea level rise or fall or indirectly by marine inundation as a result of sediment consolidation triggered by the earthquake shock, or the impact of a near-field tsunami"* (Arthurton, 1998:71). However, Arthurton (1998) fails to acknowledge the ground failure hazards (landslides, liquefaction and lateral spreading) that are associated with earthquake events and does not note the vulnerability of river environments to earthquake hazards. Nevertheless, this shows that there is previous recognition in literature of the vulnerability of coastal and river environments to the impacts of seismic events.

Ports and harbours have also been noted in literature for their vulnerability to earthquake events, due to the combination of their position upon reclaimed land and upon soils with high water tables. Ports and harbours situated at sea level are typically built upon unconsolidated material that are particularly vulnerable to secondary hazards associated with earthquakes including landslides, liquefaction and tsunamis. A prime example from the Kobe earthquake of 1995 resulted in the direct loss of US $11 Billion when 90% of the main port was destroyed (Bird and Bommer 2004, Wood and Good, 2004). A study conducted by Wood and Good (2004) looked at the ability of Geographical Information Systems (GIS) to assess the vulnerability of Port Oregon to earthquake hazards, this was part of a risk reduction planning initiative. They found that GIS had the capability to integrate natural, socio economic and hazard information in one model which made it an ideal assessment tool for holistic earthquake vulnerability and hazard management evaluations (Wood and Good, 2004). This is significant because any assessment tool needs to include both natural and socio-economic data and not just seismic and engineering data in order for effective and reliable earthquake vulnerability assessments.

1.2.4 Vulnerability

Natural hazards and the impacts that they have on human societies is considered out of the ordinary social fabric (Gaillard *et al.* 2009). As described previously in this chapter, they are unexpected and unanticipated phenomenon of which society is generally unprepared, underdeveloped and unplanned for in coping with the impacts of the hazard. Preventable harm and absent protections are of a main concern in hazard management studies today (Hewitt, 2007 and Menoni *et al.* 2012). As a consequence many societies have implemented planned measures in order to prevent natural hazards from becoming natural disasters. Such measures have driven towards controlling natural phenomenon and processes using a ‘environmental dominant approach’ which incorporates the use of engineering structures, land use planning, and hazard awareness campaigns (Gaillard *et al.* 2009).

The ‘dominant approach’ is one of two strategies used in natural disaster management, this approach treats disasters as spatial problems and explains that disasters occur because of extreme natural processes and that technical and engineering methods can counter force against them. This ‘dominant approach’ has a heavy reliance on crisis management which incorporates emergency preparedness, all in response to an event occurring. Claude Gilbert (1998) called it the “*pattern of war paradigm*” where natural agents are treated as an enemy that must be combated against (Hewitt, 2007). Unfortunately there has been an increase in disasters between the first and second half of the 20th century, showing that the 'dominant approach' has failed to reach its objective of reducing the occurrence and impacts of disasters. This letdown is the result of the failure to consider the underlying cause of disasters, which, in fact, lie in everyday society (Gaillard *et al.* 2009). Social vulnerabilities, capacities, modern rights, safe practices and protections had not been the dominant concern of disaster studies and management up until the 1980s (Hewitt, 2007).

Vulnerability is one of three concepts that have stood out in natural hazards research since the 1970s and 1980s, the other two being Resilience and Capacity. Most international policy documents now rely on these concepts to encourage disaster risk reduction, mitigation and adaption strategies (Gaillard, 2010). Vulnerability is a key term in redefining two concepts considered previously – disaster and risk (Nuno Martins *et al.* 2012). The pioneering Bruntland Report of 1987 quoted the terms vulnerability and vulnerable 47 times over 300 pages and is now used frequently in annual IPPC reports. The concept of vulnerability has been studied and applied over a wide range of disciplines which use different meanings of the concept and diverse methods of measuring it. Current vulnerability research has been more multi disciplinary, being used in both natural and social sciences and among more policy driven research (Tran *et al.* 2010).

The term vulnerability can be defined as the susceptibility to suffer damage in a potentially dangerous event due to, natural, economic or political stressors, thus it is the condition of society which makes it possible for a hazard to become a disaster (Gaillard, 2010). White *et al* (2001) defines vulnerability as a measure of risk combined with a level of social and economic ability to cope with the resulting event and highlights that vulnerability is the sensitivity to multiples stresses from differing hazard events. Vulnerability has also been defined as the degree to which human and environmental systems are likely to experience harm due to a perturbation or stress (Tran *et al.* 2010) and Kappes *et al.* 2012 has an overall definition that explains that "*disasters occur when potentially damaging natural processes interact with elements at risk and their associated physical, social, economic and environmental vulnerability*". In all the definitions of vulnerability there is an implied interaction between nature and society (White *et al.* 2001).

Present day natural hazard management approaches seek to fill the gaps that the dominant approach had in terms of disaster risk reduction and is known as the 'vulnerability and capacity perspective'. This perspective focuses on the susceptible of a society to the impacts of natural hazards instead of focussing upon constraining natural processes. This perspective focuses on social, economic, cultural and political forces that control a society's vulnerability and not on natural stressors. Social vulnerability looks at how people are at risk by their own exposure to given dangers including their bodies, homes, livelihoods, protection measures and response capacity. The controlling forces of society (governments) influence a person's ability to reduce their own risk and exposure to all of the above, against the impacts of natural hazards. According to Cutter *et al.* (2000) social vulnerability is based on several susceptibilities of the individual including the lack of access to resources, limited political power, representation, weak buildings, infrastructure and lifelines. Disaster impacts reflect social vulnerability patterns and variations in damages lie within social geography, community history, economic and political order. As such, natural processes cumulating to disasters are indiscriminate but the social processes that cause losses are discriminate (Hewitt, 2007 and Nuno Martins *et al.* 2012). Sets of indicators reflect social vulnerability including women, children, elderly, disabled, refugees and people with low wages, no savings and no stable source of income. These all reduce the ability to protect one's self from the impacts on natural hazards (Gaillard *et al.* 2009). Social vulnerability also results from inadequate social protections in the form of insurance, building and construction design standards and hazard planning, emergency and prevention measures.

Social vulnerability can be recognised in many disasters in the last few decades as there have been disproportionate casualties among certain groups of people. For example the Pakistan earthquake of 2005 caused casualties of 75,000 over half of which were children, while the Kobe earthquake in 1995 saw the loss of mostly women (60%) and elderly (53%) and in the Sri Lanka tsunami in 2005, three times more women than men were killed (Hewitt, 2007). The poor suffer the most in face of natural hazards and in the past 25 years 95% of deaths were in developing countries (Hill *et al.* 2012).

Society is highly marginalised. Marginalisation is the social process of groups of people becoming or being relegated to the fringe of society which, in turn, makes these groups more vulnerable to natural hazards. Society is marginalised in many different ways including geographically, because some places are more hazardous than others, socially, because minority groups may be more vulnerable, economically between the rich and the poor and politically as voices may be ignored by the people in power. Marginalisation tends to lead to higher vulnerability and lower capacity in facing natural hazards. Capacity is defined as the available resources and assets that people possess to resist, cope and recover from the hazards and disasters they experience. Capacity is, however, not the flipside to vulnerability, as highly vulnerable communities may display a wide variety of capacities. Capacities are endogenous to communities (available within), as they encompasses people's knowledge, experience, skills, and techniques to surviving, while vulnerability is exogenous to communities (located outside) as they encompass external wealth, resources, political systems and governance which people have no control over (Gaillard, 2010).

Gaillard *et al.* (2009) emphasised the need for community participation in natural hazard management in order to reduce community vulnerability and enhance capacity to face natural hazards. This study made a special mention to the concept of sustainable livelihoods which is explored further in their research. The term sustainable livelihood came about in the late 1980s and is defined as how people struggle to make a living and comprises their capabilities of obtaining food, water, income and assets. A livelihood is environmentally sustainable when it maintains and enhances local and global assets on which the livelihood depends. Few researches document how livelihoods interplay with vulnerability and capacity in the face of natural hazards and this study by Gaillard *et al* (2009) attempted to fill this gap.

The study looked at exploring the vulnerability and capacity of the community of Borongan in the island of Samar in the Philippines. It incorporated interviews with local scholars and government officials to identify stakeholders of resource management and explore vulnerability to natural disasters, a questionnaire based survey was sent out to households which aimed to document people's livelihoods, including patterns and strategies. Fieldwork comprised of collecting primary data and secondary written documents regarding management and planning in the area and focus group discussions were held among local residents. The paper concluded that reducing vulnerability depends upon community based disaster risk reduction programmes coupled with development objectives. Governments need to evaluate community needs and ways to sustain them over time. There is a need to empower communities with self developed and culturally acceptable ways of coping with crisis and to strengthen capacities at a community level. Sustainable livelihoods enable people to live with risk, which means that they accept natural hazards as a normal part of life (Gaillard *et al.* 2009).

White *et al* (2001) reviewed 12 key papers on natural hazards in order to examine current understanding of natural hazards, its changing focus and the value of information in reducing negative consequences of natural hazards. This study found three trends among the 12 papers: 1) there is a move towards emphasis on disasters and less on the concept of hazards, this could be due to the increasing number of disasters worldwide in the last half of the 20th century 2) a growing convergence in research and practice across hazards and 3) expansion in exploration and adaption of concepts of vulnerability, as vulnerability appeared in 7 indexes of the 12 papers. The estimated losses of natural hazards has increased in the last decade and equally there has also been an increase in scientific understanding about hazards (Menoni *et al* 2012, Nuno Martins *et al.* 2012 and White *et al.* 2001), which raises the questions: why are losses due to natural hazards not decreasing when our understanding of natural hazards is increasing? Or is the knowledge and understanding of hazards inadequate or is it just not effectively applied? There is continued concern about the limited capacity to contribute more reliable information about hazards towards effectively addressing trends in increasing losses. There is also the concern that rising occurrences of threatening natural phenomena have not been matched by enhanced community response, so that mitigation strategies in addressing threats have consequently been inadequate (Menoni *et al* 2012).

There has been a limit is assessing vulnerability, both natural and social, and in translating vulnerability assessments into usable terms for policy and decision making. Vulnerability is now a central concept in disaster research and in mitigation strategies at all scales. The paper by Menoni *et al* (2012) focuses on vulnerability as a means of approaching, describing and measuring potential hazard impacts by considering the underlying cause of effects from hazards. Social vulnerability is measured by physical and systematic susceptibility to loss and understanding that people's vulnerability is a composite outcome of exposure, resilience and adaptive capacity. The paper however, understood that vulnerability is multifaceted, with the principle facet being physical (natural and built environment). The secondary facet is social and economical. It is systematic, dynamic (shaped over time) and all facets influence one another determining overall vulnerability.

Developing holistic management strategies to reduce potential loss of life and property damage requires disaster risk reduction strategies which incorporates vulnerability assessments (Wood and Good, 2004). Disaster risk reduction incorporates better understanding of the hazards causing significant threats and the vulnerability of society, economy, built and natural environment (Kappes *et al.* 2012). The study by Kappes *et al* (2012) used indicator based methodology for multi hazard assessments. In this study vulnerability indicators were used in a GIS model. Vulnerability indicators are a qualitative approach to hazard assessments and uses social indicators to calculate overall vulnerability in a specific area to multiple hazards. The study incorporated four steps for their multi hazard methodology 1) determination of the study area, identifying hazards and hazard information, 2) determination of vulnerability indicators including building information, building surroundings and human and economic related information, 3) the factors are then weighted and vulnerability assessed and 4) the effect of hazard interaction on the overall vulnerability is determined. The advantage of assessing vulnerability using this method is that it can be adjusted to specific user needs in a multi hazard context in order to support decision making but the main disadvantage is that it requires are large input of data into the GIS model.

With regard to earthquake hazard assessments, it has been understood that earthquakes do not cause loss of life or injury themselves but rather the secondary hazards that result from earthquakes do (Hewitt, 2007). Casualties from earthquakes are mostly due to building collapses, which reflect building design standards more than earthquake magnitude or distance from the epicentre. Local bedrock, soils, water tables, vegetation and topography effect seismic motion and modify its impacts, which can be thought of as natural vulnerability. This is important for investigating sites of development as areas will have different natural vulnerability to earthquake hazards depending on their environmental features. For example the widespread liquefaction that occurred in the Kobe earthquake of 1995 was due to development on coastal alluvial soils while the landslides of the Pakistan earthquake in 2005 caused loss of life as development of communities was on steep and unstable slopes. However natural elements of vulnerability from earthquakes, tsunamis, tropical storms cannot always explain the social profiles of injuries and deaths. There are pre existing social vulnerabilities and absent protections that are more critical, suggesting that disasters are really ‘unnatural’ human made disasters.

Human environments create intervening conditions that controls the impact of a natural event such as earthquakes and recent inquiries into disasters do not attribute disasters to physical causes but mainly to failures in safety systems and responsible organisations (governments and councils). As such, deaths and damages could be prevented by greater diligence, enforcement and continuous updating of mitigation measures. This element is critical in this study because pre-existing social vulnerabilities within Christchurch did not appear to have a major influence on the spatial pattern to which the hazards associated with the earthquakes took form. It appeared that, in Christchurch, that natural vulnerability was the main driver of negative impacts. However, the components of social vulnerability still need to be included in any assessment of effects.

Research into modern disasters should not be based on understanding hazards or prevention failure during and after the event, but on what is done or not done before the event occurs. Fundamentally research should be focussed on the causes of disasters in both the natural environment and the social environment before an event occurs. There needs to be a widespread focus on promoting safe development and land use practices on land that is more naturally susceptible to hazard events in conjunction with identifying social profiles that are more vulnerable to the effects of a hazard event. Vulnerability is not a passive or inevitable condition, it is dynamic and as such can change and not wait around for an impact to occur. For example a community that lives on a river bank is vulnerable to flooding events, the community is thus located in a naturally vulnerable area susceptible to flooding, if the community decides to move further away from the river bank fringes they are actively decreasing their vulnerability to flood events. Disaster mitigation must encompass a wider context of risk reduction relevant to all those working in hazardous regions including initial development planning, government standards and legislation, council regulations and emergency preparedness and relief planning if striving towards resilient and sustainable communities is to be successful.

1.2.5 Resilience

Natural disasters are currently occurring more frequently and causing an increase in both human and economic losses. Efforts are needed at an international, national and local scale in order to reduce disaster risks. The UN International Strategies for Disaster Risk Reduction (UNISDR) defines disaster risk reduction as: "*The concept and practice of reducing disaster risks through systematic efforts to analyse and manage the casual factors of disasters, including through reduced exposure to hazards, lessened vulnerability of people and property, wise management of land and the environment and improved preparedness of adverse events"* (Djalante *et al.* 2012). Emergency management considers the concept of resilience essential for safeguarding and building safer communities (Boon *et al.* 2012) and the Hyogo Framework for Action 2005-2015 called 'Building the resilience of nations and communities' was adopted by the UNISDR in Japan, 2005 is an explicit recognition of this fact (Djalante *et al.* 2012; Hill *et al.* 2012). Increasing community resilience is important as it strives to reduce or avoid disaster impacts by reducing hazard risk and vulnerability (Guleria and Patterson Edward, 2012).

The Hyogo Framework encompassed 5 priorities:

1 to ensure that disaster risk reduction is a national and a local priority with a strong institutional basis for implementation
2 to identify, assess and monitor disaster risks and enhance early warning systems
3 to use of knowledge, innovation and education to build a culture of safety and resilience at all levels
4 to reduce the underlying risk factors
5 to strengthen disaster preparedness for effective response at all levels

The United Nations International Strategy for Disaster Reduction (2002) define resilience as "*the ability of a system, community or society exposed to hazards to resist, absorb, accommodate and to recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of essential basic structures and functions"*. Disaster resilience is seen as the ability of a group, community or nation to be able to deal with a unique destabilising situation or acts as a buffer that moderates the outcome of a perturbation to ensure benign or small scale negative consequences (Boon *et al.* 2012).

Resilience signifies reactions towards risks, shocks and stresses with the ultimate aim of survival or persistence. However, considering that resisting change may be one way, among others in preventing disasters is problematic, as it brings the back the social system to the pre-event state of vulnerability, which then leads again to a disaster. As such the following definitions employed the concept of adapting within resilience. Djalante *et al.* (2012) defined resilience as a system's ability to absorb change, to self organise, bounce back, learn and adapt while Boon *et al.* (2012) explained that resilience allows affected communities to return to normal within the shortest time possible and then adapt and learn how to discourage the disaster from happening again. Resilience is also explained as the capacity of a community to adapt to and influence the course of environmental, social and economic change in face of and recovering from hazardous events (Guleria and Patterson Edwards, 2012).

As such, resilience takes on three forms:

1 The ability of the community to absorb perturbations

2 Ability to recovery and speed of recovery as a result from stressors

3 Creativity: the ability of a social system to maintain a constant process of creating and re-creating so that the community not only responds to adversity but reaches a higher level of functioning

The concept of resilience has been studied, reviewed and adopted in various fields since its development. The term resilience was most commonly thought to have originated in the field of ecology and is here used to describe the ability of an ecosystem to absorb and adapt to change while maintaining its existing state of functioning. In the 1970s resilience emerged in the climate and disaster literature and in the 1980s was used to understand the interaction between people and the environment and the complexity of community-environment changes. In the 1990s it spread widely and is still conceptually debated today among social scientists about its application (Boon *et al.* 2012; Gaillard *et al.* 2010).

Resilience is closely related to the concepts of adaption, vulnerability and capacity (Djalante *et al.* 2012; Gaillard *et al.* 2010; Sapountzaki, 2012). One view of resilience is that it is a component of vulnerability, for example, when a social system loses resilience it becomes vulnerable and actions decreasing vulnerability increases resilience. Otherwise it is viewed as the ability to *cope* with or *adapt* to hazard stress. This includes planned preparation or premeditated adjustments undertaken in the face of natural hazards. However, the absence of vulnerability does not make one resilient as there is always a degree to which a system can continually build their capacity to learn and adapt. Other views interpret resilience as the flipside or the positive side of vulnerability (Sapountzaki, 2012) or the ability to *resist* damage and change in the face of natural hazards. The third view defines resilience as the capacity to *absorb* and *recover* from hazardous events (Gaillard *et al.* 2010).

Resisting change highlights the idea that social systems are not a component of hazard risk reduction and that engineering based measures are the only weapons available to resist hazardous events. Resisting change pre dates the idea of vulnerability, and consequently led to an increase in the use of manmade structures that sought to combat natural hazards. As such, it led to an increase in the occurrence of natural hazards and disasters. Resisting change also conflicts with development policy suggesting that post disaster reconstruction should be an opportunity to build back and develop better against the hazard, so is not a sustainable hazard management option.

The defining terms of resilience that incorporates the concepts of coping, adapting and absorbing are more appropriate terms of resilience to be used in hazard risk reduction strategies. The procedural aspect of resilience emphasises the role of learning, capacity and decision making in facing hazards which involves the re-organisation and self change in the face of perturbations. Adaptive systems do not passively respond to events, but rather they actively try to turn whatever happens to their advantage. Managing complex and co-evolving social and environmental systems for sustainable disaster risk reduction requires the ability to cope, adapt and shape change without losing options for future development (Sapountzaki, 2012). Without proactive investments, countries that are naturally and socially vulnerable to natural hazards will face significant barriers to short term recovery and long term developments.

Most of all the definitions today incorporate a stressor and the notion of adaption and a return to pre stressor levels of functioning after a disturbance (Boon *et al.* 2012). Returning to a pre stressor level of functioning can be thought of as recovery. Recovery is a significant component of resilience as the time it takes to recover and the ability to recover from a natural event relates to how resilient a community is. Recovery is usually a long and expensive process, but it is important to recover in a way that allows the community to adapt and put in place natural hazard mitigation measures which will ensure greater resilience in the future. Recovery will be an important component in this study because the effects of the Canterbury earthquake sequence on Christchurch were spatially variable indicating that resilience within Christchurch will also be spatially variable.

Without coherent risk reduction and resiliency investment, economic growth rates in countries vulnerable to disasters will decline (Hill *et al.* 2012). To foster disaster resilient communities, studies must focus on prevention, preparedness, response and recovery (Boon *et al.* 2012). The key idea is that community resilience against natural hazards is promoted through adaptive capacities enacted by individuals who form various organisations that mobilise in response to hazards (Figure 1.4). Godschalk (2003) explains that "*building disaster resilient communities goes beyond changing land use and physical facilities. It must also build capacity of the multiple involved communities to anticipate and respond to disasters*" (Boon *et al.* 2012: 388).

Figure 1.4: Example of expected growth paths with a disaster shock modelled for a 25-year planning horizon with a resiliency response scenario (Source: Hill et al. 2012: 188).

The assessment of risks is an important aspect of community resilience. Risk is a function of a hazard and vulnerability is a function of the population towards a hazard. Identifying risk exposure differences within a community is important for effective emergency planning, response and recovery. Risks from hazards are categorised by the type and severity of the hazards and their frequency of occurrence both of which are exacerbated by social and environmental factors including but not limited to development in naturally hazardous regions, urbanisation, development of poor infrastructure, poverty and inadequate environmental practices such as deforestation (Guleria and Patterson Edward, 2012). Eight elements of resilience have been identified which are essential for reducing risks from coastal hazards and in part river (river) hazard:

1 Governance
2 Coastal resource management
3 Land-use and structural designs assessments
4 Society and economy evaluation
5 Risk knowledge assessments
6 Warning and evacuation procedures
7 Emergency response procedures
8 Disaster recovery strategies

Coastal and river communities worldwide are not typically resilient to naturally recurring hazards. The degradation of coastal and river environments from human induced actions threatens food security, livelihoods, and overall economic development and well being of the coastal and riverside communities. Most countries look at coastal hazards and disasters in isolation and consider that the impact of hazards on coastal and river environments can be estimated by obtaining information on the magnitude and frequency of the hazards including the different elements at risk: population, resources, utilities and infrastructure. Assessing vulnerabilities can provide an important guide in the planning and decision making process on hazard management and to help raise public awareness of risks, which can reduce people's vulnerability to natural hazards and helps to ensure a timely and sustainable recovery in the aftermath of a hazardous event. These ideas lead to developing greater community resilience. Mitigation measures must examine the strengths and weaknesses and gaps in resilience and capacity and incorporate the building of hazard awareness and assess community vulnerability. Developing efficient environmental management and community resilience is the most effective way of reducing the long term impact of natural hazards on both the built and natural environment (Gaillard et al. 2010; Guleria and Patterson Edward, 2012)

1.2.6 Coastal and River Hazard Management

With the increased frequency and extent of natural hazards in coastal and river environments and therefore an increase in their impacts on people's lives, economies and the natural environment, there is an urgent need to reduce hazard risk through effective management in order to develop communities capable of absorbing and recovering from hazardous events. Management is a vital role in risk reduction through ensuring that accurate and reliable information is acquired through effective lesson learning and adaptive planning (Seneviratne *et al.* 2010).

The 1992 Earth Summit in Rio de Janeiro, contributed a new perspective about hazard management in the direction of including the role of engaging people to work towards a more sustainable future, particularly for the world's coastal and river environments. This would require government and non government agencies to develop policies and strategies that support a more integrated approach to hazard management in both coastal and river environments (Guileria and Patterson Edward, 2012). Unfortunately, there are many uncertainties associated with any coastal and river hazard management strategy, partly due to both the limited information available and the lack of ability to forecast critical hazards, particularly earthquakes (Kullenberg, 2001). Though there is no way of neutralising all negative impacts associated with hazards, efforts can be made in order to reduce their consequences. As such, knowledge on hazard management strategies, together with good practices and learning of lessons following a hazard event can support effective hazard risk reduction in the future (Figure 1.5). Mitigation measures, vulnerability assessments, preparedness and risk reduction activities are proactive approaches that make up hazard management strategies and any increase in proactive approaches can result in reducing negative impacts when a hazardous event occurs (Seneviratne *et al.* 2010).

Strategic management measures concerning long-term city planning aim to address extreme events and long term incremental coastal and river related hazards. They also aim to constrain the hazard and reduce vulnerability through hazard avoidance in urban development. These measures are concerned with the development of urban areas as well and the management of existing urban areas and consist of 3 main strategies:

1. To promote new urban development away from areas vulnerable to marine/river-related hazards using financial incentives and regulatory constraints as appropriate,
2. To relocate vulnerable urban population, economic activities and key infrastructure to areas of low hazard susceptibility, and
3. To enhance the standard of protection where there is existing vulnerability but where relocation is not a viable option (Arthurton, 1998).

In a New Zealand context, coastal and river hazard management is exceptionally important, due to the country's large coastal perimeter and the large extent of river environments. The Resource Management Act 1991 (RMA) is a piece of New Zealand legislation that focuses on the sustainable management of natural and physical resources, giving particular prominence to coastal planning and management. The Act provides an organisational and administrative framework for coastal hazard planning and policy development in New Zealand which fosters integration and involves all levels of government. The Act outlines the resource management functions in hazard management for Regional Councils, requiring the councils to prepare two statutory documents 1) regional policy statement and 2) regional coastal plan. These provide the objectives, policies, and methods of implementation for sustainable management of the region's resources including coastal hazards (Ballinger *et al.* 2000). Regional coastal plans and policy statements must be approved by the Minister of Conservation and cannot be inconsistent with the New Zealand Coastal Policy Statement (Rosier and Hastie, 1996).

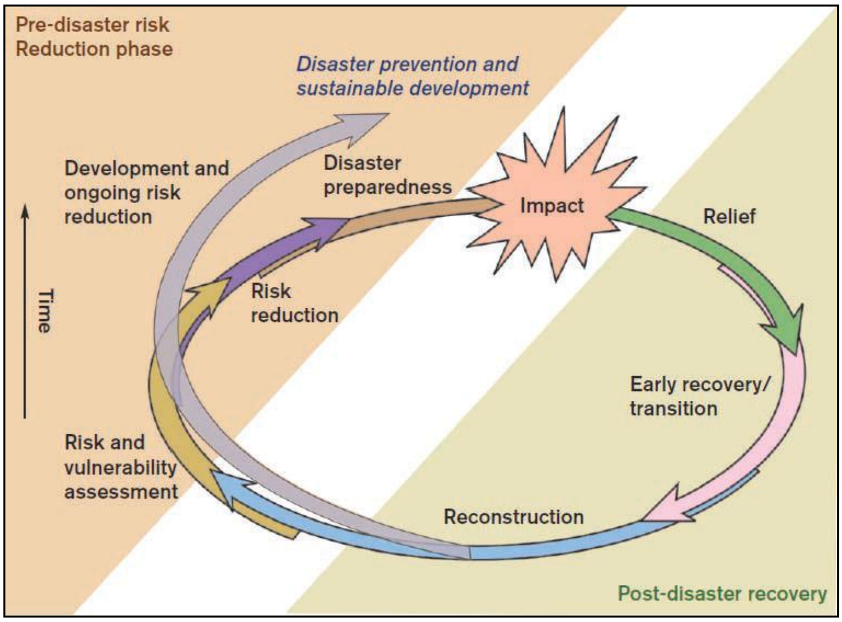


Figure 1.5: Risk Reduction Cycle (Source: Seneviratne et al. 2010: 378)

The New Zealand Coastal Policy Statement contains the general principles for sustainable management as well as policies for the management of the entire coastal environment. Policies 24-27 of the Statement deal with coastal hazards directly, Policy 24 requires the identification of coastal hazards, and Policy 25 requires the avoidance of increasing risk of social, environmental and economic harm from coastal hazards through:

- Encouraging redevelopment or land use change that would reduce the risk of adverse effects from coastal hazards for example through relocation or retreat or removal of infrastructure.
- Avoid redevelopment and land use change that would increase the risk of adverse effects from coastal hazards
- Discourage hard protection structures and promote natural defences
- Consider the potential effects of tsunami and how to avoid or mitigate them

Policy 26 requires the protection, restoration or enhancement of natural defences that protect from coastal hazards and recognise that such defences include beaches, estuaries, wetlands, intertidal areas, vegetation, sand dunes and barrier islands. Policy 27 requires the relocating or removal or existing development at risk, identify the consequences of the strategic option of ‘not doing anything’ and plan for the transition and timeframe for moving to a more sustainable approach to coastal hazard risk reduction other than hard engineering methods (Coastal Policy Statement, 2010). These hazard management policies are consistent with effective strategies observed in international literature but unfortunately New Zealand hazard management does harbour the same gaps and limitations when concerning coastal and river hazard management over a broader context.

Previous management of coastal and river hazards both in New Zealand and worldwide have not included effective mitigation or management strategies for dealing and coping with the effects of earthquakes, even when these environments have experienced a large number of damaging earthquakes in the past. Effective management must incorporate adaptive measures and it is apparent that organisations and governments have failed to recognised the significance of earthquake hazards in the context of coastal and river environments and consequently management and development in these areas has not been successful in creating resilient coastal and river communities to earthquake hazards. Accordingly the Canterbury earthquake sequence which hit the coastal and river city of Christchurch, New Zealand, highlights this gap in coastal and river hazard management literature.

The collective research into the concepts of vulnerability, resilience and management has highlighted a number of methods that have been used to study natural hazards and disasters. The use of more than one research technique provides a more complete and complementary analysis of vulnerability and resilience. It is clear that a multi disciplinary approach will be needed in this study in order to research the natural and social vulnerability of Christchurch's coastal and river environments and how Christchurch can potentially increase its resilience to seismic hazards in the future.

1.3 Gaps in Research

The field of coastal and river hazard research has advanced immensely, both nationally and internationally in recent decades. Coastal and river hazards including their potential effects and management have been well documented in most coastal and river environments worldwide and in New Zealand. However the scope within the field of coastal and river hazards has been found to be quite narrow and the events in Christchurch during the Canterbury earthquake sequence confirms this narrow view. As addressed earlier in this chapter, the Canterbury earthquakes have shown that both coastal and river environments are increasingly vulnerable to seismic hazards and not just typical river and coastal hazards. As such, there is a scope for further research into "coastal and river earthquakes", in order to gain a greater understanding about the physical characteristics of these environments that induces vulnerability to seismic hazards, towards the aim of achieving resilient coastal and river communities.

New Zealand represents a major research gap in terms of connecting coastal and river management and seismic hazard research together. New Zealand has a very long coastline that is roughly 19883 km long and not one location in New Zealand is more than 130 km from the coastline. Additionally, over 180,000 km of river landscapes has been mapped in New Zealand, making river environments extremely common throughout the length of the country. All of New Zealand's largest cities are located on the coastline or along river banks and most significantly, the country itself lies upon the tectonic boundary of the Pacific and Australian Plates (Figure 1.6). Therefore, New Zealand's coastal and river cities are extremely susceptible to seismic hazards and, as such, there is a large amount of research needed to investigate the association of seismic hazards with coasts and rivers.

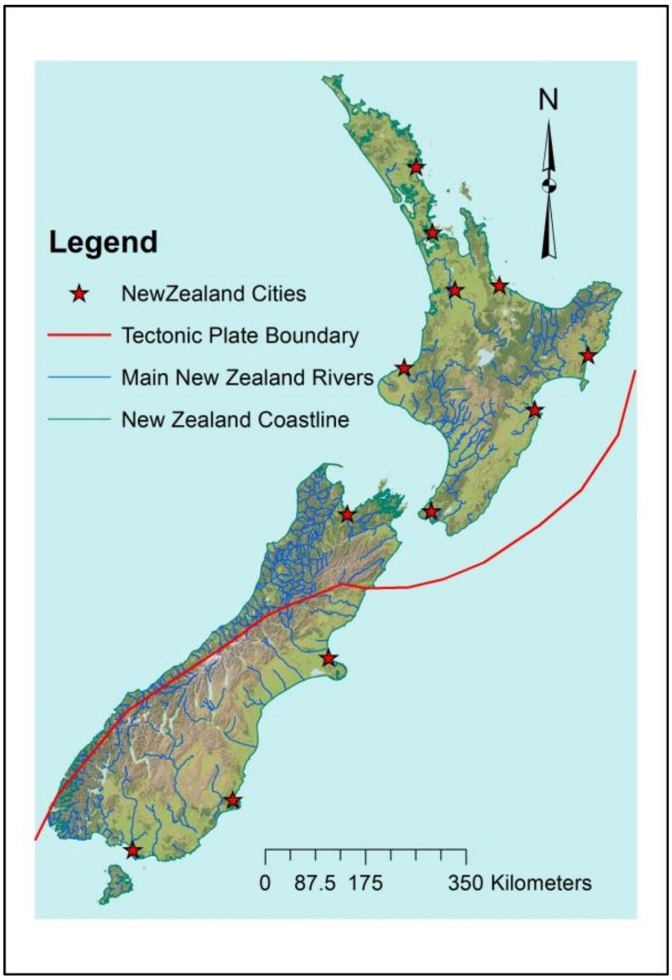


Figure 1.6: Map of New Zealand showing the main cities, the coastline, the main rivers and the tectonic plate boundary.

Research surrounding impacts of earthquake hazards on urban communities in coastal and river areas in particular has been relatively lacking. The bulk of research into earthquake effects on urban areas has been constrained to seismic and engineering knowledge, a task which has previously been completed by local government authorities who are tasked with completing seismic hazard management plans as part of their duty under the Resource Management Act (1991).

The view that coastal and river environments have played as significant a role as seismic, engineering and socio-economic factors in determining vulnerability in urban areas is a concept that has had little consideration seeing that it differs from the 'traditional' hazard management view. The events in Christchurch present an excellent opportunity to study coastal and river vulnerability to seismic hazards and derive tangible lessons for coastal and river research both nationally and internationally. Researching seismic hazards under a coastal and river lens allows for a more holistic understanding of earthquake effects as this incorporates a more inter-disciplinary approach to hazard research. This research is necessary for the purpose of future management and development of coastal and river areas and for the future development of seismic hazard management plans in New Zealand and worldwide.

1.4 Research Objectives

The primary objective of this study is to explore the natural vulnerability of coastal and river environments in Christchurch to the earthquake events and to determine the recovery patterns that arise within Christchurch in the two years following the earthquake events in order to explore potential resilience. In addition, this research aims to derive lessons that may enhance national and international understanding of the effects that seismic hazards have on coastal and riverside environments and that the vulnerability of these environments to seismic induced hazards should be considered in the development plans of areas in seismically active regions.

These objectives can be broken down into several distinct objectives:

1 To document past and present coastal and river environments within Christchurch to explain increased natural vulnerability to seismic hazards,

2 To document the effects that earthquakes and earthquake induced hazards have on coastal and riverside environments,

3 To analyse the recovery patterns in coastal and riverside areas of Christchurch to determine future resilience,

4 To derive lessons that can be learned from the experience in Christchurch to reduce vulnerability to seismic hazards in other coastal and river cities in the future, and

5 To assess ways to reduce vulnerability and increase resilience in coastal and river communities in general.

The hypothesis of this study is that coasts and rivers, past and present have played as significant a role as seismic, engineering or socio-economic factors in determining the impacts and recovery of a city, following a seismic hazard event.

1.5 Thesis Structure

The aims and objectives of this research have been presented in this chapter, along with a conceptual context and theoretical background to the study. Chapter Two is dedicated to reviewing the methodology employed in this study, by first dealing with describing the study area of Christchurch City and describing the Canterbury earthquake sequence case study. The methodology employed in this research was multi-disciplinary and used research techniques that included both qualitative research methods through the use of expert interviews and quantitative research methods though the use of digital images and Geographical Information Systems (GIS). This chapter will describe the principals, theories and techniques used for the process of data collection and data analysis for both quantitative and qualitative research methods.

Chapter Three provides a comprehensive background on the geomorphology of the Canterbury region including its geology, hydrology and tectonic setting. This is important background information as it provides the physical context for which the Canterbury earthquakes occurred. The natural environmental setting of the Canterbury region is an important element of natural vulnerability within the region and will be the main focus of this research. This study has recognised the importance of social vulnerability in disaster research as discussed previously in this chapter, but will not focus on aspects of social vulnerability due to the breadth of research that would be required. This study aims to focus on coastal and river environments and as such will need to focus on natural elements of vulnerability which are an important element in natural hazard research. Chapter Three will also provide an over view of the two most significant Canterbury earthquakes of 2010 and 2011 including seismic information of the events themselves and of their effects on the coastal and river community of Christchurch and wider Canterbury.

The next two chapters provide the results, findings and analysis of the information and data acquired. Chapter Four presents an analysis of the effects that the Canterbury earthquakes had on the natural and physical environment of Christchurch and Chapter Five presents an analysis of the recovery patterns observed in Christchurch's coastal and river environments following the earthquakes.

Chapter Six is dedicated to an integrated discussion of the key issues and lessons regarding the concepts of natural disasters, vulnerability and resilience that can be derived from the Canterbury earthquakes, which should be utilised in development and management plans of coastal and river cities worldwide. Issues currently faced in Canterbury will be identified and linkages between forces driving recovery and management decisions will be discussed. The present lessons that can be derived from the Canterbury earthquakes will be interpreted and linkages between environmental processes and development on coastal and river environments will be explored. Issues that are currently faced by regional authorities in other coastal cities in New Zealand in managing potential seismic events will be indentified and discussed. The main findings, lessons and implications are summarised in Chapter Seven, the final chapter of the thesis. Limitations of this research and areas for further research are identified in this chapter.

2 CHAPTER TWO: STUDY AREA AND METHODOLOGY

2.1 Introduction

Due to the multi-facet nature of natural hazards, they are difficult to investigate and require a combination of techniques in order to acquire a comprehensive analysis of their driving natural and anthropogenic processes. This chapter introduces the individual techniques used in this study and details the way in which they were applied. This is accomplished through describing the multiple research methods used and describing the process of data acquisition and analysis for each research method. It describes the relevant background information and attributes of each research method and explains why they were selected for use in this study. The chapter will explain how these methods were used to analyse the features of coastal and river environments and assess what makes them more susceptible and vulnerable to earthquake associated hazards.

The layout of this chapter is set out below:

- The first section of this chapter provides an overview of the study area and an overview of the case study for this research, which was the Canterbury earthquake sequence. Five research questions are set out in this section, which were used to guide the assimilation and analysis of data.
- The next section provides an overview of the research methodology including the use of triangulation and the significance of interdisciplinary research.
- The third section gives an over view of the first research techniques which was the use of expert interviews for data assimilation. This section includes an over view of semi-structured interview techniques, the importance of expert knowledge, the importance of recognising interviewer positionality and outlines how the interviews were analysed.
- The fourth section provides an over view of the use of digital images, including maps and photographs and discusses their ability to present information spatially and visually.

- The last section will look at the limitations of these techniques and reviews what could have been improved within the methodology in order to obtain more accurate and reliable data.

2.2 Study Area

The study area for this thesis is the city of Christchurch, which is located within the eastern fringes of the Canterbury Plains, in the South Island of New Zealand (Figure 2.1). It is the second largest city in New Zealand and has a population of around 350,000 (Statistics New Zealand, 2006). Smaller towns surrounding Christchurch include Kaiapoi, Rakaia, Ashburton and Timaru. The Canterbury Plains that surround and underlie Christchurch, is approximately 70 km wide and 185 km long, covering an area of 8,000 km^2 (Wotherspoon *et al.* 2012). The plains are a flat, gently inclined area of land that predominantly consists of alluvial gravel fans. These gravel fans have been formed by many large braided rivers, including the Waimakariri, Rakaia, Ashburton and the Rangitata, all of which have deposited gravel over the Canterbury Plains during the last 10, 000 years. These large braided rivers are spaced around 22-35 km apart, flowing east towards the Pacific Ocean and comprise of a catchment that exceeds 13,000 km^2 (Leckie, 2003). These rivers all originate from the Southern Alps which formed as a result of the convergence of the Pacific and Australian tectonic plate boundary and has peaks rising up to 3764 m.

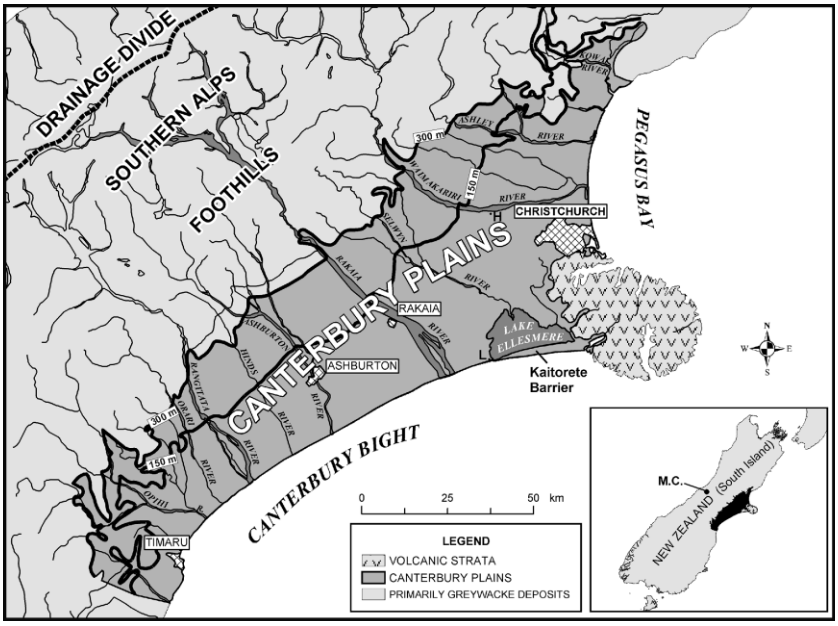


Figure 2.1: Geomorphological setting of the Canterbury Plains and Christchurch City (Source: Leckie, 2003:391)

Christchurch City reflects the major geomorphic units that underlie and boarder the region, this includes the influence of tectonics, localised volcanism, river sediment deposition and coastal erosion (Figure 2.2). Christchurch is a located on the Pegasus Bay coastline with the Waimakariri River to the north of the city and the Port Hills to the south of the city. The Port Hills are the northern most edge of Banks Peninsula which covers 1,150 km^2 and rises more than 900 m above mean sea level. Banks Peninsula is an area of volcanic origin roughly 8-11 million years old and encompasses two large harbours, the Akaroa Harbour and Lyttleton harbour (Seawell *et al.* 1992; Mcfadgen and Goff 2005; Wotherspoon *et al*, 2012). The Lyttleton harbour is significantly important to the area as it is the location of the main port of Christchurch and much of the South Island.

River and coastal processes dominate the Christchurch environment (Figure 2.2). The Waimakariri River's alluvial plains extend south-east under Christchurch and further south towards Lake Ellesmere (South of Banks Peninsula). The river's present course runs near the satellite town of Kaiapoi (north of Christchurch City) and the river enters the Pacific Ocean near the suburb of Brooklands, which sits on the southern bank of the river and is enclosed by Brooklands lagoon. Over geological time the Waimakariri River has moved between its present location and its past location, south of Banks Peninsula. The movement of the Waimakariri River has laid down river gravels continually over time and this process has built up thick layers of alluvial gravel fans that now make up Christchurch and the wider Canterbury region.

The lower banks of the Waimakariri River are artificially narrow and held in place by man-made stop banks which are intended to contain flooding and river avulsion. This measure was put in place due to multiple flooding events which saw the Waimakariri reaching the CBD four times between 1848 and 1868. The Halswell, Heathcote, Avon, and Styx Rivers are spring fed rivers flowing within Christchurch and run in the former channels of the Waimakariri. The Avon River is 26 km long and is the main spring fed river that runs through the centre of Christchurch's CBD, the Heathcote River is 22 km long and runs through southern suburbs of Christchurch and both rivers flow into the Avon Heathcote Estuary, which is a former river mouth of the Waimakariri (McFadgen and Goff, 2005).

The Avon Heathcote estuary is a predominant feature within Christchurch's river and coastal landscape. The estuary is located to the east of the city on the coastline of Pegasus Bay. It has a catchment of about 200 km^2 drained by the Avon and Heathcote rivers. It is a small (around

6 km) microtidal estuary with a tidal range of 0.2 m and varies between salt wedge and well mixed type estuaries. During dry weather conditions the Avon and Heathcote Rivers contribute 4.4m^3/sec of fresh water to the estuary and treated sewage add another 1.5m^3/sec and about 85% of the catchment of the estuary is less than 30 m about mean sea level and about 80% of this areas is currently urbanised (Mcpherson, 1979).

The Avon Heathcote estuary is a valuable resource to the Christchurch community. It was previously used as a sewage treatment facility until the establishment of the deep ocean outfall. It is also a location for prime real estate and has essential roading routes located on its perimeter. The estuary is important for recreational purposes and also has important biological habitats. The enclosing spit of the estuary, known as Brighton spit was formed by the long shore drift of sediments originating from the Waimakariri River (McFadgen and Goff 2005).

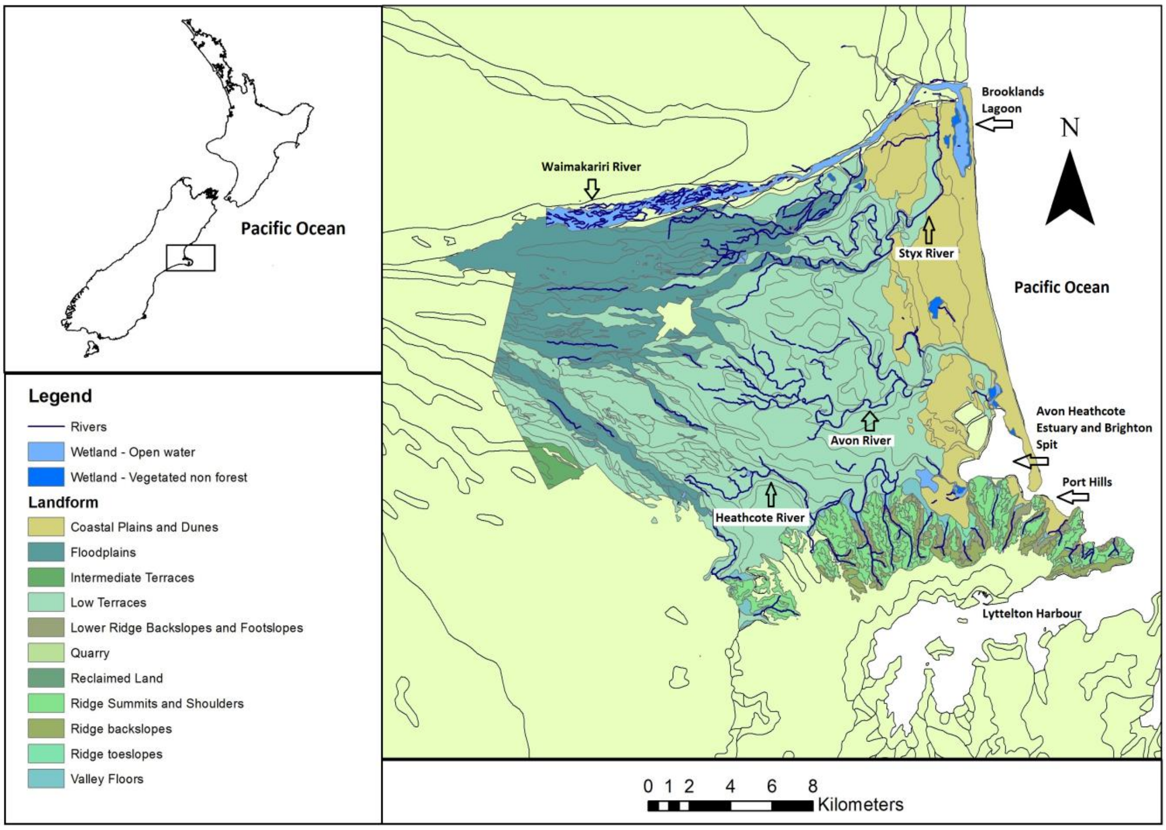


Figure 2.2: Map of the Christchurch area with a map of New Zealand in the inset. This map portrays the major coastal, river and volcanic landforms that make up the Christchurch region.

The southern coastline of Canterbury (South of Banks Peninsula) is known as Canterbury Bight. It is a transgressive coastline, dominated by mixed gravel and sand beaches and influenced by strong southerly swells. The northern coastline of Canterbury (north of Banks Peninsula) where Christchurch is situated is bordered by Pegasus Bay and is dominated by white sandy beaches. Pegasus Bay is located in the wave shadow of Banks Peninsula which means it is less impacted by the strong southerly swells that impact Canterbury Bight. This has subsequently allowed the progradation of the Pegasus Bay coastline over the last 5,000 years (Leckie, 2003).

2.3 Case Study

The Canterbury earthquake sequence was used as a case study for this research. This natural disaster event was chosen because the earthquakes significantly affected coastal and river side areas of Christchurch. This section will give a brief overview of the Canterbury earthquake sequence and the progress of recovery so far, following the earthquakes. A more detailed description of the earthquake sequences, the recovery patterns and the rebuild process will be given in later chapters. The first earthquake, known as the Darfield earthquake, struck on the 4th of September in 2010. It was a 7.1 Mw earthquake, at a depth of 10 km and centred around 30 km west of Christchurch. This earthquake caused no loss of life and few injuries but did cause significant liquefaction and lateral spreading, especially in the northern satellite towns of Kaiapoi and Brooklands. Liquefaction caused significant damage to homes and infrastructure and direct ground shaking caused damage to unreinforced masonry buildings and infrastructure within the city, but fortunately there were no complete building collapses.

However, the effects of this earthquake were minimal compared to the effects of the second earthquake which struck on the 22nd of February in 2011. This event was a smaller 6.3 Mw earthquake, but had a shallower depth of 5 km and was centred only 6 km away from Christchurch's CBD. It caused widespread liquefaction and lateral spreading in the CBD and throughout eastern Christchurch, particularly around rivers, wetlands and estuaries. The ground shaking also caused significant rock falls in the cliff faces of the coastal Port Hills suburbs. There was widespread building damage in the CBD and in the residential areas, with significant loss of life and injuries caused within the CBD. The immediate aftermath of the February earthquake saw New Zealand establish a National State of Emergency and the city's primary focus was on the response of emergency services in terms of the recovery and rescue of survivors.

The 12 months that followed the Christchurch earthquake saw the development of a government organisation called the Canterbury Earthquake Recovery Authority (CERA) that was tasked with co-ordinating the rebuild of Christchurch. The main organisations that are currently involved in the rebuild include CERA, the Christchurch City Council (CCC), the Christchurch Central Development Unit, the Stronger Christchurch Infrastructure rebuild Team (SCIRT), the Earthquake Commission (EQC) and Environment Canterbury (ECan). Non-government owned agencies are also involved with the rebuild efforts including City Care, Downer, Fletchers, Fulton Hogan and McConnell Dowell.

2.4 Methodology

When investigating complex phenomena, such as the Christchurch earthquake disaster, there is a limitation in what information can be gained using traditional quantitative research techniques alone. Qualitative research methods can offer a unique way to address complex phenomena (Hill *et al.*1997). In the Dictionary of Human Geography quantitative research is defined as “the use of mathematical techniques, theorems, and proofs in understanding geographical forms and relations” while qualitative research is defines as “a set of tools developed to pursue the epistemological mandate of philosophies of meaning” (Smith, 2000, pg 660). In recent years the use of qualitative research has been increasingly recognised as an important element in human geography and, to some extent, in physical geography (Knigge and Cope, 2006). The integration of both qualitative and quantitative research methods can greatly expand the process of data collection and the depth of data analysis (DiCocco-Bloom and Crabtree, 2006). Quantitative research provides a valuable background context while qualitative research provides a more vivid, dense and full description of the phenomena under study (Bradshaw *et al.*2001). As such, mixing qualitative and quantitative research methods can allow for the enhanced identification of issues that may not have been apparent if studied by one research approach alone (Hill *et al.*1997).

In this study a triangulated (integrated) methodology is incorporated. In a simple sense, triangulation is the use of multiple methods to study a specific problem, so as to provide a more complete answer to research questions. Complimentary triangulation involves using qualitative data to add depth and breadth to analysis and to supplement quantitative data

(Ross *et al.* 2005). By using the 'mixed methods approach' the weakness of one method can be offset by the strengths of the other, allowing researchers to see both 'context' and 'content' in a number of spatial dimensions (Samarasinghe and Strickert, 2012). Specifically this study integrates qualitative and quantitative data collection and analysis methods. This involves combining information derived from expert interviews (qualitative) and information derived from maps and photographs (quantitative).

The concept of interdisciplinary research is also a central notion in this study. Interdisciplinary research involves combining two or more academic disciplines into one activity, for example a research project. This concept is different to traditional research as it allows the researcher to cross the boundaries of different disciplines, instead of being confined within their own narrow corner of intellectualism. Allowing a research project to cross many different disciplines ensures that the research becomes more holistic and provides a broader understanding of the topic being studied. This study is interdisciplinary as the study of coastal and river earthquakes cross disciplines from seismology, geology, coastal science, river science, natural hazards and disaster science. This project cannot be positioned into just one disciplinary 'box' as it derives information and analyses information from a wide variety of disciplines. This is unlike the majority of research projects on earthquake disasters today, which usually studies the disaster from the view point of only one or two disciplines alone. This may restrict the amount of information available to the reader and it would seem more appropriate if research provided information from a wider variety of disciplines in order to ensure that certain aspects of a hazard or a disaster are not over looked.

The methodology used in this interdisciplinary study is based on the technique of triangulation which combined research methods for data acquisition and data analysis. The use of maps and photographs aims to provide a spatial interpretation of the information acquired through the expert interviews. As such, the maps and images derived from a GIS were used to support the information gained from the expert interviews in order to provide a spatial/ visual form of the information. The strength of the triangulation strategy stems from the ability of maps and photographs to visualise qualitative data and supplement data obtained from the expert interviews.

Background literature research and expert interviews were used to provide information that answered a set of pre-determined research questions. Pre-determined research questions were used to guide the analysis of data and would enable this study to achieve the research objectives set out in Chapter One. The research questions also provided a guideline for formulating the questions what were asked in the expert interviews. The research questions for this study were as follows:

Research Questions:

1 Are there specific natural features of past and present coastal and river environments that make them more vulnerable to earthquake induced hazards?

2 What were the effects of the Canterbury earthquake sequence on coastal and river environments and the built environment in Christchurch?

3 Have the Christchurch earthquake sequence influenced coastal and river environmental processes and future hazards?

4 What recovery patterns can be observed in Christchurch and how do these patterns influence the city's resilience to hazards?

5 What lessons can be learned from the Canterbury earthquake sequence that is important for other coastal cities in New Zealand and worldwide?

These research questions helped identify what information needed to be collected through the different methods of data acquisition in this study. Such a combination of research approaches is particularly appropriate for a study of this nature where not one particular source of information alone can give a complete picture of what is going on. Together with literature research, expert interviews and spatial data, it was hoped that an understanding of coastal and river vulnerability to seismic hazards could be established.

2.5 Research Methods

The first goal of this study was to set out the objectives and hypothesis of the research in order provide an outline for which the research should follow and. The second goal was to provide a comprehensive literature review on the topic of natural hazards and, in particular, earthquakes and their associated hazards. The literature review also encompassed the subtopics of vulnerability and resilience, which are key topics in the field of natural hazard research. Research into the Canterbury earthquake sequence was the next step in this study, literature was needed that pertained information on the earthquake events themselves and of their effects on Christchurch. This information is presented in Chapter Three. Background literature research on the earthquakes is a vital component of this study as information provided by literature is used to compare information provided by the experts and digital maps and photos. The literature review was constructed by using online journal websites such as SCOPUS and Science Direct which provided a source for peer reviewed journal articles.

Before the expert interviews could be conducted, ethics approval needed to be obtained from the Human Ethics Committee at the University of Canterbury. Human ethics approval is needed when any research activity in which persons are subject to experimental procedures of observations or questioning or are otherwise used as a source of information or data. This project was granted ethical approval for expert interviews by the Human Ethics Committee, the approval number was HEC 2012/92 and a copy of the approval letter can be found in the Appendix 1.

The next stage of research was to acquire experts that would be willing to be a part of an interview. Formal requests for participants were sent to known experts through email and a snowball effect facilitated further experts to be identified and requests sent out again. More comprehensive detail of the expert interviews is provided in later sections of this chapter. Once the interviews were conducted the recordings were then transcribed. The transcribed interviews were then sent back to the participants so that they had the opportunity to look over the information that they had provided, made sure that the information was correct, and make any changes or additions. This part of the process was put in place to make sure that the information obtained had not been skewed by the listening or the transcribing process.

Data analysis was the next stage in the methodology. The expert interviews were analysed for common themes and general consensus, with the ultimate aim of determining whether or not the experts supported or opposed the research hypothesis and background literature. At this stage data analysis also incorporated the collection and/or production of maps derived from GIS and photographs that depict earthquake related information. Maps and photographs were used with the aim of representing information about the Christchurch earthquakes and the geomorphology of Christchurch, in a spatial context.

This spatial representation of data was used to support the information obtained from the literature review and the expert interviews. When maps were collected or produced, they were analysed to see whether or not the information they portrayed could back up the verbal and written information provided from previous research and the experts. These maps and photos were also used to support the research hypothesis in a visual format. Below is an outline of the methodology, including the research process and methods used at each stage of the study (Figure 2.3).

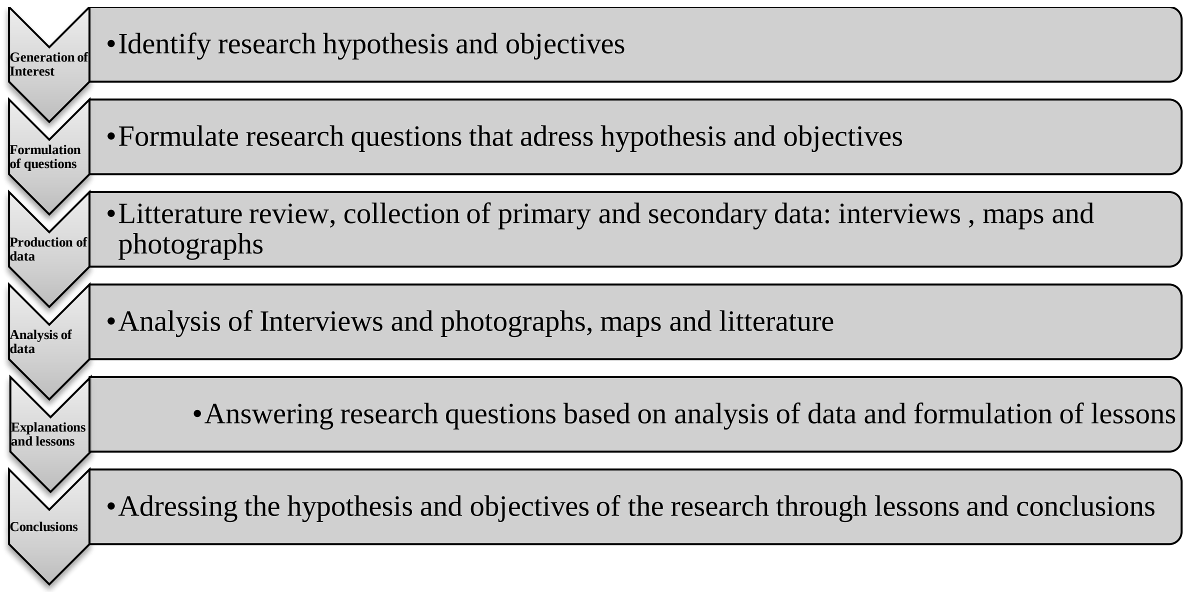


Figure 2.3: Diagram outlining the research methodology

2.6 The Role of Expert Knowledge

This research involved gathering information and primary data through identifying and interviewing key experts. Expert interviews refer to interviews with individuals who are targeted as specialists, or are responsible for implementing policy and making decisions, as opposed to the general public, residents, consumers or voters. Expert interviews are intended to help researchers understand how decisions makers or professionals view a particular problem or topic (Sovacool *et al.* 2012). The types of experts targeted in this study included scientists in research organisations and in local government. Expert judgement is not intended to be a substitute for scientific research, but used to define the current state of knowledge and the range of uncertainty surrounding the research topic. Using expert interviews as a primary form of data collection makes knowledge available that would otherwise not be accessible through quantitative research methods alone. It also demonstrates the current pool of expert knowledge on the topic and is able to reveal areas of greater or lesser agreement between experts, which may help drive future applied research (O'Neill *et al.* 2008).

In depth expert interviews are most useful when the objective is to understand complex phenomenon that are not able to be simplified into a few key variables (Sovacool *et al.* 2012), as was the case for assessing the vulnerability of coastal and river environments to earthquake associated hazards. Expert opinion is used in the interpretation of scientific evidence and, when used in combination with other sources of information, can be of value for management decisions where uncertainty is high and where there is an absence of adequate knowledge or lack of empirical data to assess uncertainties (O'Neill *et al.* 2008 and Page *et al.* 2012). It is used in many different areas such as risk analysis, reliability analysis, and knowledge acquisition. It was particularly useful in the Christchurch earthquake scenario given how recent the events were and the slow process of research on these events being studied, analysed and published.

Expert interviews can be applied to many other environmental problems where expert opinion is required to fill knowledge gaps, such as the extrapolation of scientific understanding to larger scales (Page *et al.* 2012). Expert interviews and opinions are increasingly used for the interpretation of scientific evidence and assessing evidence and uncertainty. Examples of such studies include the examining of aerosol forcing (Margan, 2006), the possibility of west Antarctica ice sheet collapsing (Vaughan and Spouge, 2002), climate change adaptation in Asia (O'Neill *et al.* 2008), the impact of livestock grazing on birds (Martin *et al.* 2005) and forest ecosystem change (Morgan, Pitelka and Shevliakova, 2001). Expert opinions and knowledge is acquired in many different forms such as absolute or relative numbers (estimates, ranges or distributions), words (qualitative descriptions or relationships or sources of uncertainties) and graphical forms (diagrams and conceptual models), thus the design of the interview questions must take into account the purpose and types of information that it to be collected (Page *et al.* 2012).

Experts were selected for their knowledge and role in regards to the research topic as well as their willingness to serve as teachers and translators for the researcher. As noted in literature, the sample of participating experts should be fairly homogenous and share critical similarities related to the research topic (DiCocco- Bloom and Crabtree, 2006). Selecting experts in this study was based on the process referred to as purposeful sampling, where experts are selected for interviews purposefully, and not at random, in order to maximise the depth and richness of data to address the research questions. Purposive sampling was used to identify key experts that represent different aspects of the topic in question. A critical stakeholder analysis framework was also adhered to, which requires a broad spectrum of respondents from government, councils, and academia (Sovacool *et al.* 2012).

There are also a number of other decisions that must be made prior to conducting interviews with experts such as: the number of experts needed, the choice of experts, the degree of interaction between the researcher and the experts and whether or not achieving consensus is the goal or whether the variation in opinions is more valid (Page *et al.* 2012). Interviewees were selected based on the critical stakeholder analysis framework and included experts in coastal, geological and seismological science, engineering, and in councils and government organisations involved with Canterbury earthquake sequence. The number of experts for the study depended on who was willing to contribute to the project and consequently, there was no quota. However, in order to facilitate comparative analysis, the more experts interviewed the more sufficient the data collected will be. While there is no ideal number of participants needed for qualitative research, Beach et al. (2001) notes that below four, it can be difficult to generate theory with much complexity and conversely above ten, the complexity and volume of data is said to become difficult to manage.

The concept of data saturation was also applied to regulating the number of participants. Data saturation is the process where data collection and analysis eventually leads to a point where no new information emerges, signalling that data collection is complete (DiCocco- Bloom and Crabtree, 2006). As such, interviews were continued until there appeared to be saturation of the information supplied by the experts and no more than 10 experts would be interviewed in order to control the volume of information the experts would provide.

The goal of interviewing was to see if there was a general consensus among the experts on the research questions and if there is a variation of opinions, the goal was to understand why that variation existed. Disagreements among experts may provide important information and can be crucial when it is known that the experts' opinions have been used in important decision making.

2.6.1 Expert Interviews

Because there are many organisations involved in the rebuild of Christchurch and because of the abundance of knowledge that experts have concerning earthquakes and the Christchurch environment, professional interviews appeared to be the most appropriate form of collecting qualitative data for this research. Interviews are one of the most common strategies for collecting qualitative data and the purpose of professional interviews is to contribute to a body of knowledge that is both conceptual and theoretical and based on the knowledge and understanding of the expert being interviewed (DiCocco- Bloom and Crabtree, 2006).

Reliable data from what people say should not be inherently less worthy than reliable data from any other source, which is why expert interviews should be considered an appropriate form of data collection in physical geography. Some interviews are used to test a prior hypothesis, often using a very structured interview format where the questions and answers are standardised or coded for a more quantitative analysis, whereas other semi- structured interview techniques seek to explore information, meanings and perceptions to gain a better understanding of the phenomena under study and to generate a hypothesis from this information. The latter interview technique requires interviews which encourage the participant to share their in depth knowledge and explanations of phenomena while leaving the interpretation and analysis of the information to the researcher. Over all the process of qualitative research needs to be open to discovering new concepts and ideas about the research topic as not all ideas may have been considered prior to constructing interview questions.

Expert interviews were a primary tool for data collection in this study. The primary purpose of using expert interviews is to clarify and deepen the understanding of the research questions and therefore a semi-structured interview technique was employed. Semi- structured interviews were organised around a set of predetermined, broad and open-ended questions. This enabled participants to provide more detailed answers and allowed for other questions to emerge from the dialogue between the participants and the researcher (Sovacool *et al.* 2012). The questions for the interviews were sufficiently focussed so that a relatively homogenous group of participants would have shared knowledge about the topic. The nature of semi-structured interviews often results in the altering of questions as the researcher learns more about the topic and additional questions were progressively added to the interviews in this study in order to gain further insights. However, an attempt was made to keep all original research questions among the interviews so that complete comparisons of answers could be made during the data analysis phase of research. The interview questions are provided in Appendix 2.

Interviewees were first contacted by email to ask if they would be willing to participate in a professional interview that formed part of a Masters Research project. Participants who were first emailed were chosen based on their expertise and who they work for. The participants needed to have knowledge of either coastal or river environments, geology, earthquakes or their hazards such as liquefaction, effects of the earthquakes on Christchurch or the recovery of Christchurch City. The participants that were willing to participant then organised a date, time and location that was most suitable for them to conduct the interview. The final collection of experts that were interviewed is outlined in table 2.1. There were several steps that took place in the beginning of each interview that introduced the participant to the research project. These steps are described below:

- Before starting the interview questions the research project was first explained to the participant, including its objectives, and how the participant could contribute to achieving those objectives.
- The participant could then look over the consent form and ask any questions regarding the information supplied on the form.
- The participant were informed that the interview had been approved and by the Human ethics committee of the University.
- Every interview began with the participant providing information on their professional title, role and background. This helped with validating why they were chosen to participate in a professional interview for this research.
- The participant was encouraged to give whatever information, knowledge or opinions they had on the interview questions and were advised that there was no right or wrong answers.
- At the end of each interview, key points were gone over again to make sure that the participant was happy with the information they have provided. They were also told that they would be given a copy of the video/audio file of the interview so that they could review it at their own leisure.
- All participants were told that they could further communicate ideas and information towards the research or make any changes to the information they had provided.

Table 2.1: List of experts selected for interviews, with information on their expertise, who they work for and the date of the interviews.

Name	Company	Expertise	Interview Date
Justin Cope	Environment Canterbury	Coastal resources scientist	30/8/12
Sonia Giovinazzi	University of Canterbury and SCIRT	Civil and natural resource engineer	10/8/12
Graham Harrington	Christchurch City Council	Surface water planner	30/8/12
Murray Hicks	NIWA (National Institute of Water and Atmosphere)	Coastal and river geomorphologist	23/8/12
Matthew Hughes	University of Canterbury and	Civil and natural resource engineer	6/8/12

	SCIRT		
Robert Kirk	University of Canterbury	Coastal process geomorphologist	9/8/12
Marion Irwin	Environment Canterbury	Hazard analyst	30/8/12
Shamus Wallace	Tonkin and Taylor	Engineering geologist	27/8/12

2.6.2 Positionality and Reflexivity

The term Positionality refers to the awareness of a researcher to their own background and how the people or experts being researched may perceive them. The Positionality of a researcher can be based on their own class, gender, race or educational background. Positionality can play a central role in influencing the research process both in the field and in the final research product (England, 1994). Reflexivity refers to the process of thinking through the power relationship between the researcher and the person being researched and how this relationship may affect the interpretation of data and knowledge production. Impartiality, objectivity and neutrality prevent the researcher from being biased in their interview questions and contaminating the data being gathered, however previous literature has stated that aiming to do this in research is incredibly difficult and almost impossible (Rose, 1997). Incorporating positionality and reflexivity into the research process allows for critical analysis of the researcher and the research context that allows for a more flexible approach to field work and the analysis of data. This in turn allows the researcher to be more open to anything that challenges their theoretical position which in field work inevitably does occur. Overall incorporating reflexivity and Positionality into the research process takes into account and recognises the researcher's position as well as that of the research participant's and this should be considered throughout data analysis (Rose, 1997).

Despite the possible bias that may occur from the nature of power relations between the researcher and the experts in the interviews, the study design dictates the need for qualitative data collection methods in order to adhere to the methodology of triangulation. Because the interviews in this study are not based on obtaining personal, social or cultural information the concepts of positionality and reflexivity do not appear to be as significant for this study, however this study does recognise that they are important concepts in qualitative research so the research process will still aim to consider and incorporate them. The aim of the interviews in this study is to obtain scientific information from experts. Scientific information is not data that is subject to being ‘personally delicate’ and therefore the way that experts perceive the researcher should not contaminate the data that they provide.

Aside from positionality and reflexivity there are many phenomena that can lead to biased results in using expert interviews and the following is an identification of some that are relevant to this study. Interviewing for scientific information can suffer from a drawback when experts are encouraged to speculate, or be influenced by the researcher’s own opinions. Information from the experts can still be influenced by how the expert views the positionality of the researcher. The framing of questions (phrases used and the order of the questions) is important as it can have significant effects on the expert’s answers. Researchers need to be aware of their own preconceptions which may influence the way questions are framed or reframed to suit the researcher’s own ambitions and for this reason the scope and specificity of questions is crucial (Page *et al.* 2012).

Researcher’s Positionality:

Researcher’s Background: I grew up in Auckland, New Zealand, in a small coastal suburb called Howick. I lived close to the beach in Howick for 18 years, until moving to Christchurch 5 years ago, to attend university. At University my main subjects of interest have been in geomorphological processes and natural hazards. I have been an advocate of environmental protection since high school and have a passion for wanting to protect New Zealand’s coasts and rivers from inappropriate development. I enjoy activities that include fishing, surfing, swimming and camping, which indicates that the coast is also important to me for not only nostalgic and educational reasons but also recreationally.

Researcher’s Bias: Because of my background I have a strong affiliation with the coastal environment and to some extent river environments (as I understand how important rivers are to the New Zealand environment and economy). As such, I believe that studying coasts and rivers is important and that there needs to be continual research done into understanding these dynamic environments. While undertaking research into the effects of the earthquakes on coasts and rivers and trying to understand coastal and river vulnerability to earthquake hazards, I must at all time control this bias so that it does not interfere with data in a way that corrupts or invalidates.

It is also important to avoid ambiguity in the questions so that experts can comment on exactly the same phenomena. Biased information is still a significant issue to be considered in scientific information. The experts are sourced from different educational and organisational backgrounds which is a positive aspect because the information they provide will be from varying disciplinary backgrounds. This means there would be a variety in the answers of the experts which is a positive aspect, but their answers may not be holistic as they can only draw knowledge from the background that they have studied, which in turn creates educationally biased answers. As such, it is important that this study recognises the potential biases during the interviews both from the researcher and the expert participants and any bias should be considered in the analysis and interpretation of the data acquired and this can be helped by the concepts of positionality and reflexivity.

2.6.3 Interview Analysis

Combining expert knowledge for analysis depends on whether the methodology sets out to reach a consensus among experts or if it strives to retain variability in the opinions (when the variation is seen as valid) (Page *et al.* 2012). The methodology in this study aims to reveal consensus among the experts with regards to the research questions in order to determine whether or not expert knowledge supports the hypothesis of this study.

Page *et al.* (2012) describes two approaches that can be used to categorise and combine expert opinions 1) the mathematical approach and 2) the behavioural approach. The behavioural approach attempts to generate agreement among experts. This approach involves combining experts' opinions into a distribution of opinions. This method is used because a combined distribution of opinions produces a better appraisal of the data than individual distributions of opinions. Combined distributions can be considered as some sort of consensus which also retains the breadth of opinions. The researcher must assume that variations in expert responses are all valid and must aim to retain the full variation of opinions as all expert opinions are equally valid so that no reliability or expertise weighting is employed in the analysis.

Because interview analysis had the objective of identifying the emergence or verification of concepts through expert consensus, the practice of coding was appropriate. Coding interview data supports the identification of concepts and constructs opinion distributions through the reliable categorization of data (Ross *et al.* 2005). The practice of coding qualitative data incorporates the process of evaluating and organising data in an effort to identify and understand themes in the text and helps the researcher to identify categories and patterns which can in turn be investigated through additional data collection and analysis. Coding is both a process of data reduction (making hundreds of pages of notes easier to grasp) and data analysis (evaluating data and, looking for consistencies and inconsistencies, identifying patterns) the researcher is analysing their findings (Knigge and Cope, 2006).

Interview analysis for this study followed a qualitative research analysis process known as thematic analysis. The process of using thematic analysis to analyse interview data is clearly set out in Braun and Clarke (2006) and involves searching across a data set (transcribed interview) to find repeated patterns of meaning. Thematic analysis provides a rich description of the entire data set and allows the researcher to get a sense of important themes across the entire data set and is useful when investigating an under-researched area (Braun and Clarke, 2006). The analysis for this study used specifically theoretical thematic analysis where themes and patterns are identified using a bottom down approach, where the identification of themes is driven by the researcher's analytic interest and codes are created for specific research questions. The themes that were identified among the data set were semantic themes, these are themes that are identified at an explicit or surface meaning, and in other words the researcher is not looking for any meanings that go beyond what is said by the interviewee.

Thematic analysis uses the process of open coding. Open coding is used to review and identify segments of data. Open coding is the process of reducing data to small sets of themes that appear to describe the phenomenon under investigation. The process of open coding is when the data that has been collected is divided into segments and then scrutinised for commonalities that could reflect categories or themes. Once the data has been categorised it can then be examined for properties that characterise each category. The identification of meanings and patterns within the data is accomplished through making comparisons and looking for similarities and differences between comments and in this way similar comments can be grouped together to form categories. In this study the data was categorised and organised into segments through identifying patterns of opinions and then interpretive statements were made about the patterns of either consensus or variation in expert opinions. In this way coding qualitative interview data is similar to the process of making maps as both involve dealing with data rich environments, then simplifying them and making sense of patterns and processes (Knigge and Cope, 2006).

The process of thematic analysis as outlined in Braun and Clarke (2006):

1) Transcription of verbal data into a written data set
2) Researcher familiarises themselves with the data set

    a) Reading and re-reading
    b) Taking initial notes on the data and identified common themes
    c) Ended this phase with a highlighted transcript of common themes
3) Generating initial codes
    a) Created an initial list of themes that were in the data set
    b) Codes identified a feature of the data that appeared interesting for analysis
    c) Coding was part of analysis as data was being organised into meaningful groups
    d) Compiled quotes from the data into codes
    e) Ended this phase with a list of codes and coded quotes
4) Searching for themes
    a) Analysis at the broader scale of themes rather than codes
    b) Involved sorting out all the different codes into potential themes
    c) Used mind maps and tables to sort common codes into groups
    d) Ended this phase with a collection of candidate themes
5) Reviewing themes
    a) Refinement of candidate themes
    b) Made sure all coded quotes within a theme for a coherent pattern
    c) Ended this phase with a good idea of what the themes are, how they fit together and the overall story that they tell about the data
6) Naming and defining themes
    a) Created a thematic map of the data set (See Appendix 3).
    b) Thematic map shows all themes and how they link together
    c) Accounted the quotes and indentified what was interesting about them and why
    d) For each individual theme a detailed analysis was generated. This included naming the theme, defining the theme, finding literature to back up the theme, adding quotes to back up the themes. Analysis of the theme needs to identify the story that the theme tells and how it fits into the broader story of the entire data set.

2.7 Digital Images

Because this study aimed to incorporate triangulation into its methodological design, visual images including digital photographs and GIS derived maps were used in conjunction with the analysis of expert interviews. The purpose of incorporating photographs and maps into the methodology is to enable primary data and information to be portrayed in a visual format and support the data acquired from the analysis of literature and expert interviews. Visual images have been used widely in natural hazard research and in particular in hazard vulnerability research. For example Brown *et al.* (2006) looked at how the use of advanced computer visualisations can communicate coastal erosion and sea level rise issues to the public in order to improve public awareness of the changing risks. Peters-Guarin *et al.* (2012) demonstrated that local knowledge of flood hazards can be structured systematically into a geographic information system (GIS) to create more effective disaster reduction practices and Rawat *et al.* (2012) identified the vulnerable areas for river-line and flash flood hazards and socio-economic and environmental risks and its mitigation through the use of GIS.

The term visualisation has been informally used to describe any developed method for displaying data and can range from paper maps to the use of GIS for exploring and analysing data (Knigge and Cope, 2006). Brown *et al*. (2006) defined visualisation as a computer generated image that provides a visual representation of physical space or environment with the intention of facilitating interpretation. Visual images are commonly communicated in the forms of charts, diagrams, maps, graphics and 2D and 3D computer models (Sheppard, 2005). Digital photographs and maps produced using a GIS are also forms of simple visualisation. The rationale for using visual images is that they have the ability to raise environmental awareness through communicating massages and information effectively through spatial representation of data. This is because visual images have a cognitive advantage over written and verbal forms of information in regard to what the human brain can understand and interpret (Sheppard, 2005). As such, maps and photographs uniquely contribute to critical geography theory by becoming a tool for representing and supporting other forms of data in a spatial context.

The continual explosion of computer power and possibilities associated with new technologies for representing information is providing a wide variety of techniques for those with an interest in displaying visual information. The application of visual images has traditionally focussed on the production of two dimensional maps which follow standard principle cartographical design (Pettit, 2011). When using GIS, researchers can explore data in order to identify themes and processes, raise new questions and begin to build theories. Techniques that link GIS based maps with other data sources such as charts, graphs or ethnographic data including digital photography and text can provide rich, contextual data for consideration and analysis (Knigge and Cope, 2006). Maps are now used for exploratory data analysis and knowledge derivation and map makers now have a wide range of tools and techniques available and can produce maps for a wide range of specific tasks (Dykes, 2000).

Maps can be considered a spatial interface to geographic information that map users browse by specifying views of available data as desired and required. However it is quite simple to distort the truth in communicating traditional two dimensional maps and one must maintain a healthy scepticism when considering any manipulated digital representation of reality. There are a number of strengths and weaknesses in the application of visual images for communicating information and visual images can be evaluated on a number of criteria including their accuracy, representation, visual clarity, interest, legitimacy, access, framing and presentation (Pettit, 2011).

Dynamic maps provide known information with the intent to communicate with, engage and inform a public audience. All maps should be designed for a particular purpose and should be judged on their ability to achieve their communicative objective. Geographic information as a form of information visualisation emphasises the development and assessment of visual methods designed to facilitate the exploration, analysis, synthesis and presentation of geo-referenced information (Dykes, 2000). Visualisation is a communication medium most people utilize on a daily basis and as a consequence it has the potential to enhance communication with decision makers and stimulate the willingness of the public and stake holders to engage with a particular issue (Pettit, 2011). The disaster risk reduction sector has come to recognise the value of geospatial information such as digital photography, satellite imagery, GIS and GPS (global positioning systems) and using them to map vast quantities of geospatial information on natural hazards and their impacts on the environment and on social vulnerability (Peters-Guarin *et al.* 2012). Visual imagery is found to be crucial in environmental planning and is used in a number of ways to support both operational and strategic decisions (Pettit, 2011).

Field work for this study involved the collection of digital images that provided a visualisation of the impacts that the earthquakes had on Christchurch city. The photos presented in this thesis are a combination of photos that have either been taken by the researcher personally or taken by others, who have allowed their photos to be a part of this study. The photos aim to show the impacts of the earthquakes on Christchurch city and in particular to show the impacts to areas surrounding rivers and the coastline. As such, when undertaking field trips to collect images, the main areas of interest were within the CBD, around the Avon River, around the eastern suburbs and around the Avon-Heathcote Estuary. The photos taken on these field work exertions were taken around a year and a half after the February 2011 earthquake, which means that they are images portraying the lasting effects associated with the disaster and the ongoing recovery efforts.

For this reason, research into obtaining images directly after the earthquakes was needed, in order to portray the effects of the earthquake directly after the shaking. This was needed because the most significant hazards associated with the earthquakes, happened directly after the shaking occurred. The photos selected from the research were chosen because they portrayed significant effects to homes, buildings, roads and other infrastructure. Particular interest was taken in making sure photos showed impacts to areas that are located close to rivers and the coastline. Digital images were chosen to be an integral component of this research as they are able to communicate effectively what the effects of the earthquakes had on Christchurch and in particular the coastal and river environments. These images not only help portray immediate and long term earthquake effects but also assist to support information provided from literature on the earthquakes and information provided by maps and expert interviews.

This study utilised the collection of maps derived from a number of secondary data sources that portray information about Christchurch and the Canterbury earthquake sequence. This included:

- past and present coastlines and rivers
- geology and hydrogeology
- fault lines and aftershock sources
- earthquake induced liquefaction and lateral spreading in Christchurch
- earthquake induced damages to buildings and infrastructure in Christchurch
- land elevation changes
- recovery land zoning and rebuild land categories

The spatial data layers were collected using online portals: Land information NZ data service http://data.linz.govt.nz/, LRIS portal http://lris.scinfo.org.nz/ and Koordinates http://koordinates.com. These data layers included:

- Christchurch geology
- Christchurch city soils
- New Zealand Coastlines
- New Zealand Rivers

- New Zealand Topography
- Christchurch boundary lines

The collection of data sources was exported into *ArcGIS* where maps were then created and analysed for patterns and observing correlations between areas of significant earthquake effects and particular geomorphological features. These maps were also used to analyse and support information gained from expert interviews, for example the main themes that come about from the interviews such as liquefaction are supported by or compared to a map of liquefaction in order to verify the information from the experts.

The objective of this research was to establish whether coastal and river environments have a greater vulnerability to earthquake hazards and whether these environments have played an integral part in generating greater negative effects in particular areas of Christchurch. The aim of this stage of data analysis was twofold: first to produce and/or collect visual maps and photographs from the secondary data sources that portray the overall observed negative effects associated with the Canterbury earthquakes on Christchurch and to understand whether or not coastal or river geomorphological features have contributed to generating larger earthquake effects observed in particular areas. Second was to analyse the maps and photos and make interpretations regarding the observed patterns and draw conclusions based on these observations. The next aim was to observe whether the conclusions made from the visual maps and photos are in either consensus or differentiate from the conclusions drawn from the expert interview analysis. This facilitates the methodological process of triangulation to be completed as one method of data collection supports or opposes the other and thus consensus or variation in the conclusions from the experts and the visual maps can be justified.

2.8 Limitations of Methods

There are a number of limitations to qualitative research using interviews including the validity of data acquired. In this context, validity is concerned with the confidence that can be placed on the information provided by experts and the extent to which this information can be generalised. There are two types of validity that can cause limitations to the data acquired and the analysing of data:

1. Internal validity: Bias of the researcher and the experts causing internal validity of the researcher’s observations of the acquired data.
2. External validity: Difficulty in generalising observations to theory

A major weakness is determining if the researcher is getting a representative picture of what they are studying, is due to the bias of both the researcher and the experts, which can distort information acquired and analysed. An expert interview, as a method thus suffers from subjectivity, and relies heavily on the integrity and intellectual honesty of the researcher. Because a researcher has their own positionality, there is always potential for bias when the researcher both conducts the interviews and analyses the information. Positionality may cause the researcher to only consider the aspects of the information given by the experts that they consider interesting or relevant and may possibly disregard important information that is important but has been disregarded because of the researcher's own knowledge of the research topic. A researcher must maintain an open mind and regard all information provided by the experts and not let their personal opinions on the topic cloud their judgment on what information is more important than other pieces of information. A researcher will also have personal characteristics that will either enhance or diminish different rapports with expert participants which may influence the amount of information the expert divulges (Gaber, 1993).

The information provided by the experts themselves may also be a limiting factor in this method of data acquisition. This is because, the information provided by the experts may be opinions or speculations and not based on factual knowledge of which they have studied. Over confidence of experts is also a possible form for bias as experts tend to be over confident in their knowledge, however this is less of a problem when within their own area of expertise. Specialised expertise however, does not eliminate bias, as the extent of the expert's knowledge does not necessarily equate to their ability to provide coherent and unbiased assessment of the interview questions (Page *et al.* 2012). Ensuring that the selected experts exhibit a full range of different backgrounds will help to improve internal validity, and also aids in supporting information provided by an expert that is an opinion on information outside of their own area of expertise.

Other limitations are to do with sample size, as the number of experts interviewed in this study is relatively small and the selection of participants was not random and subsequently results many not be generalised. Due to time constraints the number of experts interviewed was not large and this is a limitation because a larger sample group would have had a larger variety of backgrounds, which would have provided more information from different areas of expertise. This would have aided in providing more holistic information and would have enhanced the interdisciplinary component of this study.

There are a number of limitations when working with data sets in order to create maps in a Geographical Information System. Firstly, the input data layers to a GIS may be of varying standards which means that a certain degree of error propagation may be inevitable in the output maps created. The degree of access to data sources and layers is also at times extremely difficult. There are copyright problems and legal positions that makes newly created data unavailable. This was particularly true when trying to obtain data layers for the Canterbury Earthquakes as information regarding liquefaction and land damage, was and still is regarded as contentious.

2.9 Summary

This chapter detailed the methodology employed in this study, first dealing with describing the study area and the case study of the project and secondarily describing the techniques and theories used for the process of data collection and data analysis. A summary flowchart illustrating the timeframes of the methodological process was presented.

The methodology employed in this study incorporated the technique of triangulation and was inherently embedded within the notion of interdisciplinary research. The methodology included the use of both quantitative and qualitative methods for collecting and analysing data and over a number of different academic disciplines. Triangulation allowed the research process to obtain greater depth and breadth during the data collection and analysis phase and the weakness of one research method could be offset by the strength of the other.

The qualitative research technique employed in this study involved the use of expert interviews. The use of expert interviews and the role that expert knowledge plays in data collection was clarified in this chapter. Expert interviews were used to answer the research questions because experts hold knowledge pertaining to the geomorphology, the coastal and river environments, and the effects of the earthquake on Christchurch as well as the recovery of the city. Positionality and reflexivity are two concepts that required attention during the collection of data via the interviewing process. Qualitative researchers must be aware of their positionality when conducting and analysing interviews and must also be reflexive (open and transparent) about their research process in order to develop robust and valid conclusions. Interview analysis involved the combining of expert information and opinions in order to demonstrate consensus among experts with regard to the interview questions. The analysis involved open coding techniques that aimed to identify patters in expert opinion through the categorization of data and scrutinising the data for commonalities that reflect themes.

This chapter also described the use of GIS and photographs in this study. The collecting and generating of photographs and maps was used for the purpose of displaying the qualitative information provided by the interviews in a visual and spatial format. Maps were used supplement the information obtained from the expert interviews and is able to display information that would otherwise be conceptually difficult to interpret and understand if presented in a written format alone. The visual forms of data employed include photos that portrayed the effects of the earthquake on the Christchurch area and also included maps derived using Arc GIS that had the intention or portraying coastal and river geomorphological features of Christchurch in conjunction with the effects of the earthquake, in order to observe patterns that could explain or underpin reasons for significant earthquake induced effects.

The results gained from these techniques and analyses are presented in the following chapters.

3 CHAPTER THREE: CASE STUDY

3.1 Introduction

As highlighted in Chapter Two, the physical environment of Christchurch City is profoundly influenced by its spatial relationship with significant geomorphological features. These features include the proximity of Christchurch to the Southern Alps, the Pacific Ocean, Banks Peninsula and the many large braided rivers that run across the width of the Canterbury Plains (Figure 3.1). As such, Christchurch is dominated by extreme geological and geomorphological processes, primarily, climatic, tectonic, coastal and river (Leckie, 2003). This chapter will describe the geomorphological setting of Christchurch City and the wider Canterbury region. This includes information regarding the geology and hydrology of the area. The chapter also describes the tectonic setting including earthquake sources and historic earthquake events. The previously predicted earthquake risk potential, and the effects, consequent after the 2010 and 2011 earthquakes on the physical and built environment of Christchurch will also be addressed. Describing the geomorphological and tectonic setting of the Canterbury region is necessary in order to provide a context for which the impacts of the Canterbury earthquake sequence occurred.

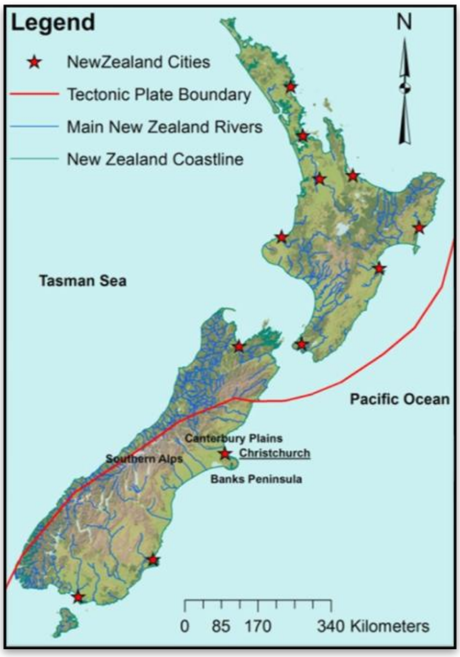


Figure 3.1: Map showing the main geomorphological features that surround Christchurch and other New Zealand cities

In conjunction with describing the physical setting of Christchurch, this chapter will also describe the details of the Canterbury earthquake sequence and describe the immediate aftermath in Christchurch. The September 2010 Darfield earthquake will be discussed first followed by a discussion on the February 2011 Christchurch earthquake. In both sections the details of the earthquake events will be covered, including their timing, location, magnitude and fault type. The impacts of each quake will be discussed in detail including information on impacted buildings, infrastructure, lifelines, land and the natural environment.

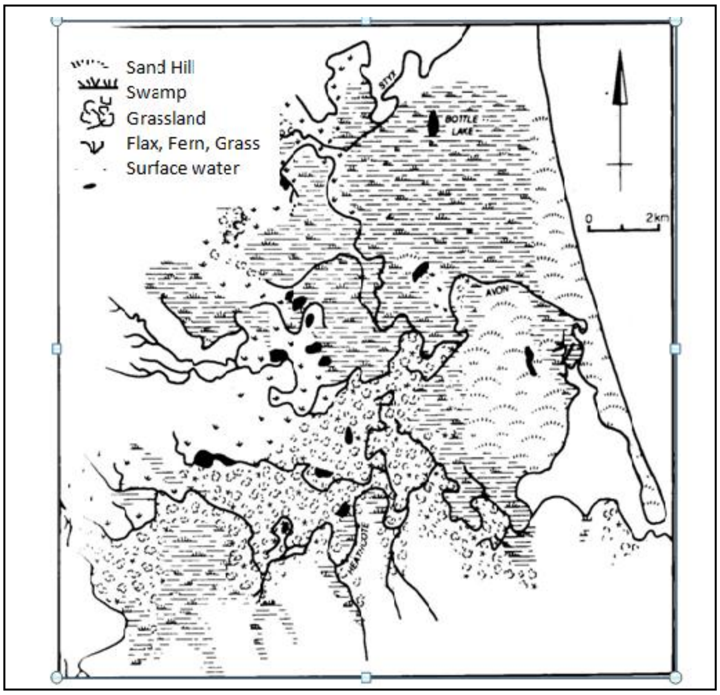
3.2 The Geomorphological Setting of the Canterbury Region

Understanding an area's geomorphological features is imperative when trying to establish how natural hazards operate and influence the surrounding natural environment. Before earthquake impacts on coasts and rivers can be addressed there needs to be an understanding of the geomorphological makeup of coastal and river environments within a tectonically active region. As such, this section will describe the physical geomorphological setting of Christchurch and the wider Canterbury region. This will begin with an overview of what the Christchurch environment looked like, historically when European settlers first arrived. Then looking back further in time, the chapter will also describe the geology and hydrology underlying the region. This section aims to uncover which distinct geological and hydrological features of coastal and river environments combine to increase vulnerability of particular areas of Christchurch to earthquake associated hazards.

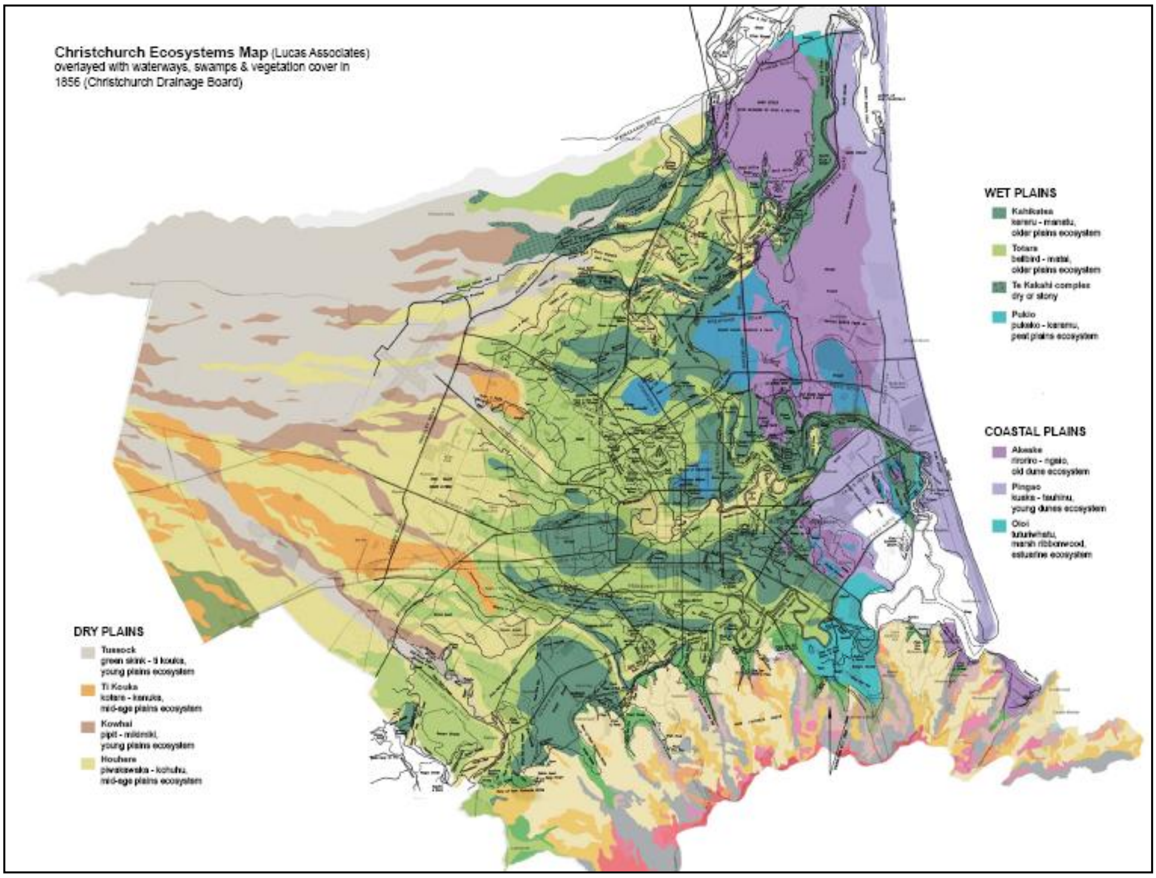
Early maps indicate that pre urban Christchurch consisted of small pockets of dry land with predominantly wet marsh land and many shallow swamps and ponds (Figure 3.2). This large swampy area was drained by a dense network of small meandering streams and was separated from the sea by a large belt of sand dunes (Figure 3.3). Christchurch's ground surface water, in its original state comprised of three small coastal rivers; the Styx, Avon and Heathcote, which are fed by underground springs at their headwaters. Estuaries, numerous other spring-fed streams and coastal wetlands also made up Christchurch's surface water features (Watts, 2005). Early settlers had to contend with extensive swamp land and one of the first organisations established in Christchurch was the Christchurch Drainage Board. The drainage board was tasked to completely drain and infill the Christchurch area, making it ready for the City's development. Modern water and soil maps illustrate the diversity of surface water environments in the Christchurch area including gravel outwashes from the Waimakariri

River system, windblown loess soils from the Port Hills system and coastal silt and sands from Pegasus Bay (Macpherson, 1979).

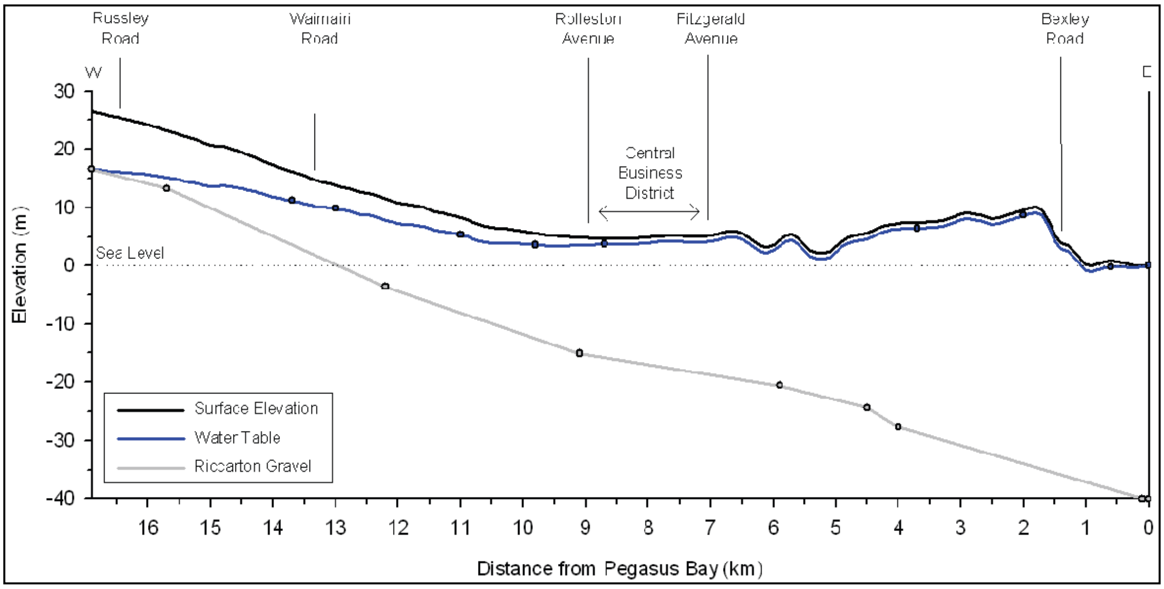
Underlying the city are large ground water aquifers. The groundwater system between the Waimakariri River and Christchurch provides the pathway for water to move from the Waimakariri River to recharge the aquifers. The Avon River is spring fed from these groundwater reservoirs and groundwater recharge from the Waimakariri influences discharge of the Avon River springs through pressure effects in the confined aquifers (White, 2009). The meandering stream beds of these rivers and their tributaries incise and rework surficial sediments of Christchurch creating local meanders, channels and over bank deposits of silt, sand and peat. The ground water table affecting the upper 10-20 m of sediments is generally between 2-3 m below the surface in the west of Christchurch and 0-2 m below the surface in the central and eastern suburbs of Christchurch (Jacka and Murahidy, 2011) (Figure 3.4). Christchurch has an abundant water supply through its rivers, streams and very active ground water regime and in order to access this water it is estimated that nearly 10,000 wells have been sunk within the Christchurch urban areas since the 1860s. Today Christchurch has only a fraction of the wetland area it once had prior to human settlement with only a few protected wetlands remaining, including Bexley Wetland (east of the CBD) and Travis Wetland (North-East of the CBD).



3.2: The 1856 ‘Black Map’ of Christchurch, showing the former extent of surface water, sand dunes, swamps and different vegetation types (Source: The Christchurch Drainage Board).



3.3: Modern interpretation of the 1856 'Black Map' indicating the extent of coastal plains and wetlands (Source: Lucas Associates, 2011)

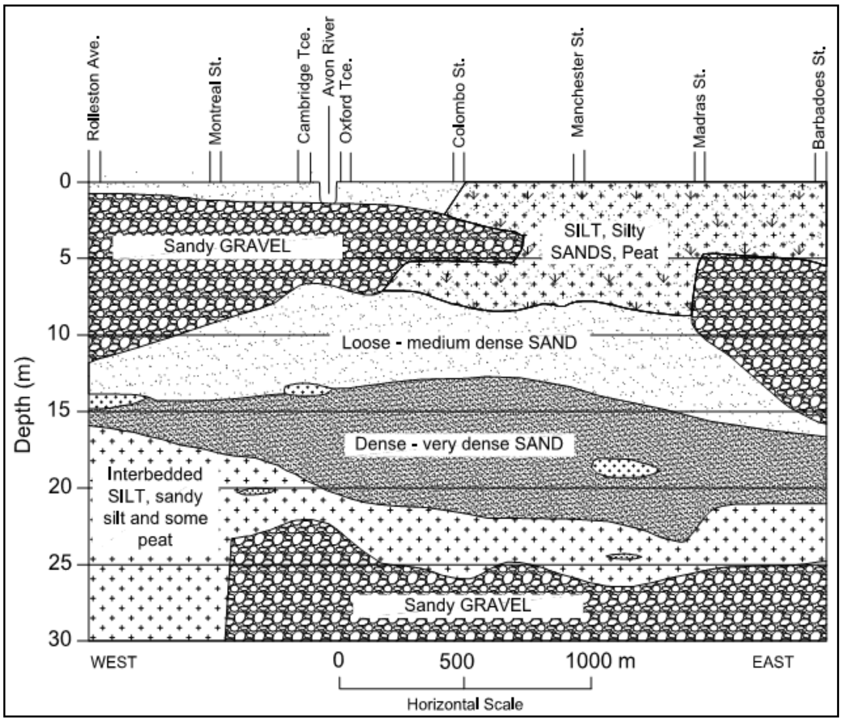


3.4: General profile of shallow Christchurch soils indicating thickness of recent alluvial soils and water table depth along an east-west cross section (Source: Cubrinovski and McCahon, 2011:40)

Alluvial deposits comprising sand, silt and gravel have been laid down by rivers and streams over the Canterbury Plains over the last 10,000 years. These fan shaped wedges of alluvial sediment are formed where rivers or streams emerge from hilly terrain onto low gradient valley floors or plains. These deposits are typically poorly sorted and range from several metres thick to major aggradational deposits many tens of metres thick, which can mask older geologoical features including historic fault ruptures (Forsyth *et al.* 2008). Three main alluvial fans make up the surface of the Canterbury Plains. In the lower Waimakariri River region, the two youngest alluvial fans are the Yaldhurst surface and the Halkett Surface which lie upon the Springston Formation. These surfaces are recognised as being of post-glacial age. The third alluvial fan is the oldest and known as the Darfield surface which is thought to be an outwash fan of two major advances of the Otira glaciations.

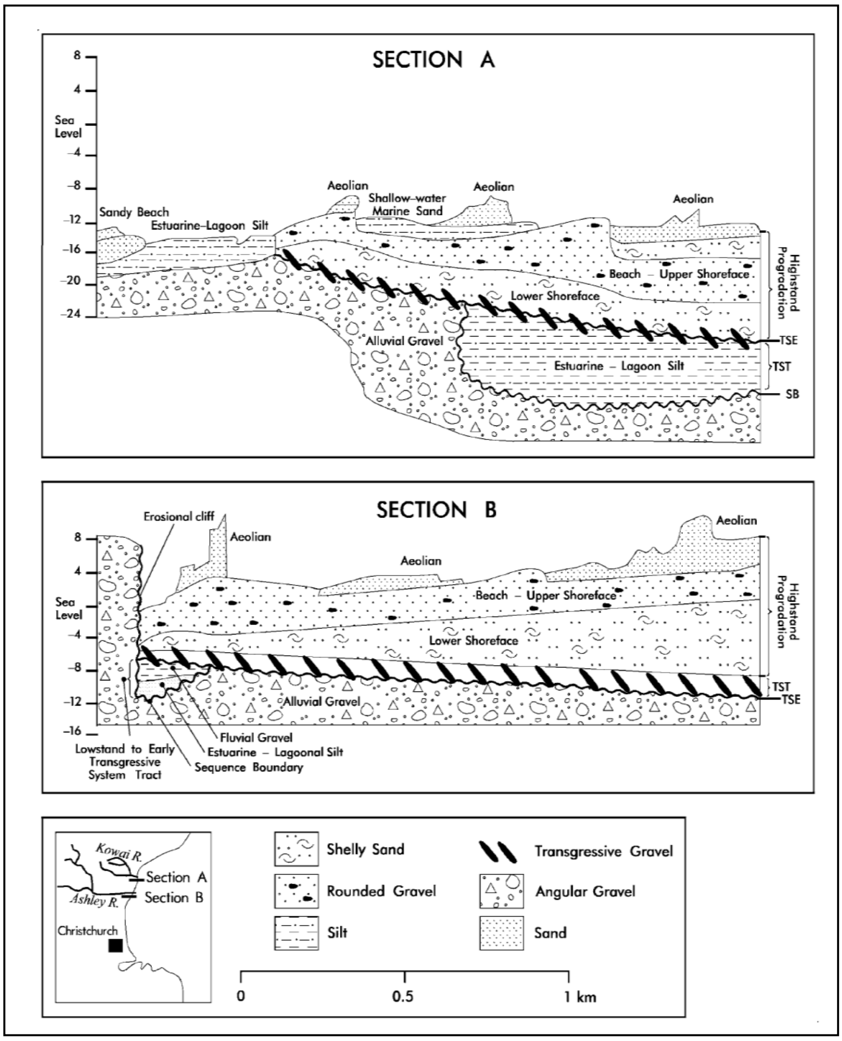
To the east of the Springston Formation is a wedge of dominantly fine-grained beds known as the Christchurch formation and Christchurch is built upon these sediments. The Christchurch formation formed during post glacial sea level rise when the sea transgressed westward over Christchurch city, depositing marine sediments over the peats and silts that had already been deposited by earlier estuarine environments (Wotherspoon *et al.* 2012, White, 2009). Accordingly the sedimentation of eastern and central of Christchurch over the last 10,000 years can be divided into three parts, the first part is an estuarine and swamp component which comprises of silts and peats formed 10,000 years BP, the second part was a marine component comprising of offshore shelly sands deposited 6,000 years BP and the third was a coastal components which comprises of progradational peats, silts, dune sands and gravel channel deposits formed during the stable sea level of the past 6,000 years to present day (Figure 3.5 and 3.6).

Gravel filled channels within these fine-sediments indicate temporary incursions of the Waimakariri River. Towards the head of the postglacial fans, rivers began to entrench into the glacial outwashes of the inland plains and the resultant sediment from these rivers contributed to coastal progradation. Over the last 6,000 years the coastline has prograded from its most inland position that ran south from Papanui, through Fendalton and around the western edge of Hagley Park towards its present location (Wilson. 1976). Underneath Christchurch, surface postglacial sediments have a thickness between 15 and 40 m and they overlie at least 300-500m thick sequence of gravel formation interbedded with sand, silt, and peat layers (Curbrinovski, Henderson and Bradley, 2011).



3.5: Representative subsurface cross section of Christchurch CBD along Hereford Street (Source: Elder and McCahon, 1990).

These gravel and marine sediments lay upon 200-300 m of volcanic rock overlying a greywacke base at about a depth of 1 km. To the south of the city the sediments become shallower against the weathered volcanic cone of Banks peninsula and the Port Hills are mantled with loess soils over the basalt rock (Centre for Advanced Engineering, 1997). The shallow soils of the Christchurch formation in western Christchurch comprise gravels, sands and silts and in eastern Christchurch comprise of sand, silt, and peats from swamps, estuaries, lagoons, dunes, and beach deposits (Figure 3.5). The Christchurch formation surface soils overlie the Riccarton gravels which are the upper most gravel layer of an older age (14,000-70,000 years old) and contain the top most aquifer with elevated water pressures. The thickness of surface soils upon the Riccarton Gravels is smallest in the west (~10 km thick) and increases in thickness towards the coast, where thickness of the Christchurch formation reaches ~40 km thick (Cubrinovski, Henderson and Bradley, 2011).



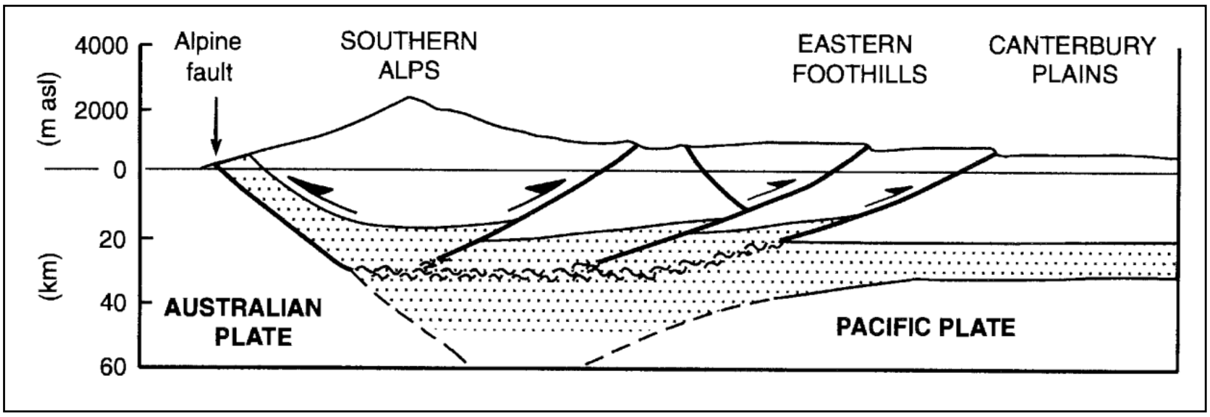
3.6: Cross section along the highstand progradational coast of Pegasus Bay, north of Waimakariri River mouth. Stratigraphy modified from Shulmeister and Kirk (1993) (Source: Leckie, 2003:405).

3.3 The Tectonic setting of Canterbury

New Zealand has a unique tectonic setting that provides a wide range of potential earthquake sources. The boundary between the Australian and Pacific Plates lies through the middle of the country. To the north along the Hikurangi trench the Pacific Plate is subducting from the east at 40 mm/year and to the south and along the Pusegur trench the Australian Plate is subducting from the west at 35mm/y. In the middle of New Zealand the plates are locked together forming the Alpine fault in the South Island and the formation of the Southern Alps (Goff *et al.* 2008). The Canterbury region, to the east of the Southern Alps experiences complex and widespread active earth deformation directly related to its proximity to the Australia-Pacific plate boundary.

The main features of the South Island plate boundary zone include the Marlborough fault zone north of Canterbury and the Alpine fault zone to the west of Canterbury. The Alpine Fault forms a linear feature through the length of the South Island extending onshore for about 420 km along the west side of the South Island and offshore for about 200km at the south west tip of Fiordland. Geological data shows that the majority (70-75%) of plate boundary motion occurs along the narrow high strain zone associated with the two locked plates forming Alpine Fault and the remainder of boundary motion occurs across 150-200 km wide zone of the Southern Alps and into western Canterbury (Goff *et al.* 2008 and Pettinga *et al.* 2001) (Figure 3.7). The residual strain rate within the Canterbury block extending from the Southern Alps and into Christchurch is estimated from GPS-derived velocity fields to be ~2mm/yr or ~5% of the plate motion budget (Kaiser *et al.* 2011).

The nearest known active faults to Christchurch are the onshore Ashley fault, located 30 km to the north of Christchurch and the offshore Pegasus Bay Fault, located about 30 km north east of Christchurch. The maximum magnitude of earthquakes on faults surrounding Christchurch has been assessed through geological evidence and magnitudes generally increased with distance away from Christchurch (Centre for Advanced Engineering, 1997). In 1997 Environment Canterbury instigated and Earthquake Hazard Risk Assessment Study for the Canterbury Region. The paper by Pettinga *et al.* 2001 described the first stage of this study which reports on the main earthquake sources found within Canterbury.



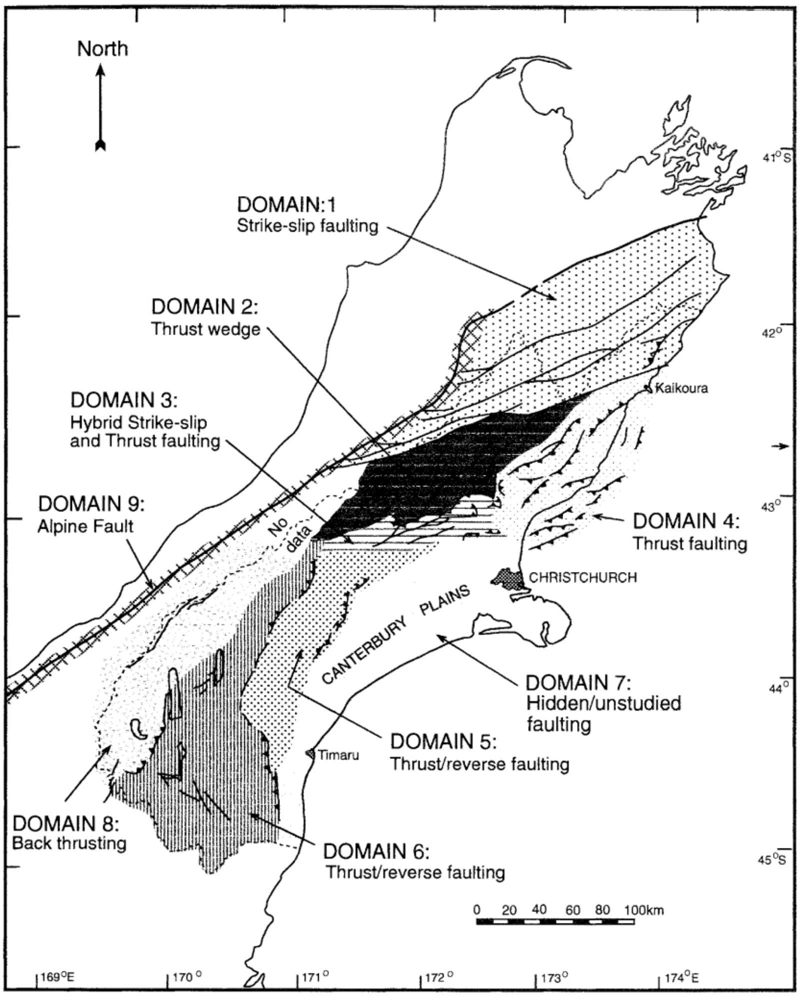
3.7: Schematic over view of the tectonic plate boundary of the Australian plate and the Pacific Plate (Source: Pettinga et al. 2001: 286)

The paper identified 90 active faults surrounding and within the Canterbury region. These sources were characterised into nine domains and each domain provided a basis for probabilistic seismic hazard assessments (Figure 3.8).

- Domain 1 – Marlborough Fault Zone: the most active earth deformation zone in the Canterbury region.
- Domain 2 – West Culverden Fault Zone: includes 3 different faults.
- Domain 3 – Porters Pass-Amberley Fault Zone: includes 3 faults reflecting the latest phase of plate boundary zone widening in the late Pleistocene.
- Domain 4 – North Canterbury Fold and Thrust Belt: includes 5 faults from the coastal hills southwest of Kaikoura and the NE Canterbury region.
- Domain 5 – Mt Hutt-Mt Peel Fault Zone: this is the Southern Alps and eastern foothills zone of a single thrust fault.
- Domain 6 – South Canterbury Zone: this domain is at the edge of the Southern Alps in South Canterbury, east of the MacKenzie Basin and south of the Rangitata River.
- Domain 7 – Canterbury Plains Zone: this zone would be the most relevant to this study.
- Domain 8 – Southern Alps Zone

Domain 7 has active earth deformation beneath Quaternary alluvium gravel fans of the Canterbury Plains. Recorded seismicity beneath the Canterbury plains indicates that the area is subject to some neotectonic activity. However, the northwest Canterbury plains have no obvious active fault or fold structures and very limited and generally poor quality seismic reflection data is available for this region. The study indicated that “hidden earthquake” sources in this area are in need of further study.

Domain 8 – Southern Alps Zone: this zone extends east from the Main Divide of the Southern Alps and includes the Main Divide fault and the Ostler Fault zone. Deformation is dominant in this zone and is considered of fundamental importance in terms of uplift within the Southern Alps, due to the locking of the Australian and Pacific Plates. Domain 9 – Alpine Fault Zone: this fault is the longest active fault in the South Island, extending 650 km from offshore south of Milford Sound. It is the bonding fault of the Southern Alps and has maximum uplifts rates in the central section estimated at 7-10 mm/yr. The fault dips east beneath western Canterbury (Pettinga *et al.* 2001).



3.8: Map showing the seven domains of earthquake sources in the South Island (Source: Pettinga et al. 2001: 288).

Previous earthquakes felt in Canterbury include the 1994 magnitude Ml 6.7 and the 1929 magnitude Ms 7.01 earthquakes on the Arthur’s Pass Fault. Other earthquakes felt in the region include the 1929 Ms 7.8 Buller earthquake and the 1901 Cheviot earthquake with a magnitude of Ms 6.9 (Brabhaharan *et al.* 2005). Historic earthquakes have also been recorded to hit closer to Christchurch including the Christchurch earthquake on the 5th of June 1869, this earthquake was believed to have centred beneath New Brighton with an approximate magnitude of 5.6. The other earthquake struck on the 31st of August 1870, south of Banks peninsula, near Lake Ellesmere with an estimated magnitude of 5.8 (Environment Canterbury and Pettinga *et al. 2001*). Consequently, the entire Canterbury region is exposed to a number of earthquake sources (~90 sources) all of which can generate a seismic hazard for the city of Christchurch (Figure 3.9).

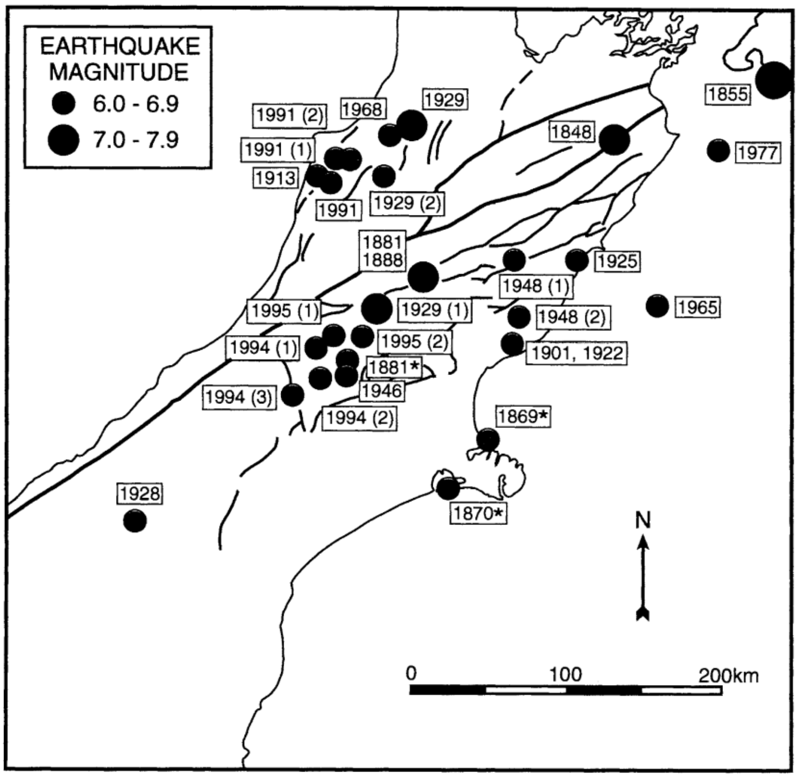


Figure 3.9: Map showing historical earthquakes of magnitude 6-7.9 in and surrounding the Canterbury Region. * The two significant earthquakes close to Christchurch City (Source: Pettinga et al. 2001: 290)

An Earthquake Risk Assessment Study was completed by Opus International Consulting ltd in 2005 for the Christchurch area. This study intended to identify earthquake sources surrounding Christchurch and comprehend the likely impacts of a major earthquake on the city. The assessment was commissioned by Environment Canterbury as they needed to identify the likely impacts and consequences of a major earthquake in order to fulfil its hazard mitigation and emergency management functions. The Resource Management Act 1991 requires local authorities to identify, assess and mitigate the effects of natural hazards in their region. The assessment conducted a refined literature review of the possible earthquake sources within Canterbury and defined four possible earthquake scenarios for Christchurch. The assessment then reviewed the possible impacts of these earthquake scenarios on the city including effects on people, infrastructure and lifelines. The four earthquake scenarios that were defined for the Christchurch region were a:

1 Moderately large earthquake in the Canterbury foothills or North Canterbury with a postulated magnitude of up to 7.5

2 A very larger earthquake on the Alpine Fault with a postulated magnitude of up to 8-8.5
3 Earthquakes centred close to Christchurch with a postulated magnitude of up to 6.6
4 Earthquakes from hidden Canterbury Plains Faults – the assessment notes that this scenario should be discussed with seismologists as part of risk assessment

The above four hazard scenarios had been generalised into one scenario event that was applicable to a range of earthquake magnitudes with epicentres at various distances from Christchurch city by the Centre for Advanced Engineering Lifelines Group in 1997. The "*Risk and Realities"* report that was subsequently written by the group, postulated that the earthquake hazard risk in Christchurch had a 150-year return period with shaking intensities of Mw 5.0-6.9. This return period was chosen as it large enough to cause very significant damage but was not such a remote probability as to be discounted as irrelevant (Centre for Advanced Engineering, 1997). This coincided with Stirling *et al.* 2001 where their Probabilistic Seismic Hazard Assessment Model ascertained levels of earthquake shaking intensities of 0.2-1 g can be expected across Canterbury with return periods of 150, 475 and 1000 years.

3.4 Earthquake Definitions

The magnitude M or Moment magnitude Mw, of an earthquake relates to the energy released by the earthquake at the epicentre (source of the earthquake). Generally the effects of the earthquake decreases with increasing distance away from the epicentre. The effects of an earthquake are measured on the Modified Mercalli Scale (MM/MMI) of felt intensity. This is a descriptive scale which reflects the intensity of shaking according to damage and felt effects. The Magnitude M/Mw of an earthquake is a single measurable value at the epicentre where as the Mercalli MM/MMI of an earthquake varies with distance from the epicentre (Centre for Advanced Engineering, 1997).

The peak ground acceleration PGA is a measure of earthquake acceleration on the ground and can be expressed in g (the acceleration due to Earth's gravity, equivalent to g-force). Unlike the Mw scale it is not a measure of total energy release but rather how hard the ground shakes in a given geographic area. It is like the MM scale but is measured by instruments such as accelerographs and not personal reports. The Peak Horizontal Ground Acceleration is the most commonly used type of ground acceleration used in engineering applications and is used to set building codes and design hazards risk scenarios. In an earthquake damage to buildings and infrastructure is a result ground motion and rather than the magnitude of the earthquake (Douglas, 2003).

The shaking intensity at a site is affected by the ground conditions. An assessment by Opus International, 2005 noted the potential variability of effects of ground shaking on the relatively soft sediments of a soil profile and points out that shaking intensities could be increased from 0-2 MMI units in soft sand compared to bedrock. The Centre for Advanced Engineering notes that, ground shaking intensities also vary with soil depth with sites of deep soils generally showing amplified motion and compared with sites on shallow rock. As described above, Christchurch is situated over geologically recent deposits of alluvial gravel laid down by rivers and deposits of fine marine sands and silts. The sediments beneath central Christchurch are deeper and finer than those to the south of the city. Thus ground intensities in central and eastern Christchurch are postulated to have higher ground shaking intensities than those in western and southern Christchurch.

Earthquake shaking in the Christchurch region will be markedly affected by the deep and relatively fine sediments underlying the city particularly in the top 30 m and this creates changes in the ground acceleration at any frequency. Because Christchurch is located near a saturated, sand and silt rich coastline, it is at potential risk from earthquakes induced hazards including liquefaction, and liquefaction induced lateral spreading. An over view of earthquake terminology used in this study is provided in the table below (Table 3.1).

Table 3.1: Table of earthquake intensity measurement definitions

G	When there is an earthquake, the forces caused by the shaking can be measured as a percentage of gravity or percent g
M	A number that characterizes the size of an earthquake – based on a measurement of the maximum recorded motion recorded by a seismograph
MW	Moment Magnitude Scale - measures the size of the earthquake in terms of the energy released

MM	Modified Mercalli Scale – used for measuring the intensity of an earthquake by measuring the effects of an earthquake - the intensity is not determined by magnitude
PGA	Peak Ground Acceleration – a measure of earthquake acceleration on the ground – it is not a measure of energy release (magnitude) but how hard the earth shakes in a given geographic area.
MMI	Modified Mercalli Intensity Scale - generally deals with the manner in which the earthquake is felt by people

3.4.1 Liquefaction

Liquefaction is the process that leads to a soil suddenly losing its strength as a result of ground shaking however, not all soils will liquefy in an earthquake event. Soils that will liquefy include sands and silts that are quite loose in the ground, such soils do not stick together in the same nature that clay soils do. These unconsolidated sands and silts need to be below the water table, so that all the space between the grains of sands and silt are filled with water. Dry soils above the water table do not liquefy. When an earthquake occurs the shaking is so rapid and violent that the sand and silt grains try to compress the spaces filled with water, but the water pushes back and pressure builds up until the grains effectively 'float' in the water (Ambraseys and Sarma, 1969; Obermeier, 1996).

Once the grains 'float' the soil loses its strength, it has liquefied and soil that has liquefied then behaves like a fluid. Liquefied soil, like water, cannot support the weight of whatever is lying above it including surface layers of dry soils, concrete floors of building or concrete roads. This means that the liquefied soil under that weight is forced up into any cracks and crevasses it can find including those in cracks of concrete and dry soils above, it flows out onto the surface as boils, sand volcanoes and rivers of silt (Figure 3.10). In some cases the liquefied soil flowing up a crack can erode and widen a crack to a size big enough to accommodate a car (Figure 3.10). Near streams and rivers, the dry surface soil layers can slide sideways and on the liquefied soils, this is called lateral spreading, it can severely damage a building and typically results in long tears and rips in the ground that look like classic fault line fractures (Ambraseys and Sarma 1969). Liquefaction is known to re-occur numerous times in the same site, if it happens once that does not mean that it will not occur again in the future. Damage from liquefaction is commonly seen as:

- Flotation of buried structures (figure 3.11)
- Lateral spreading of the ground on gentle slopes particularly around water bodies
- Settlement of large areas due to consolidation and liquefied soils being ejected through surface cracks
- Foundation failures and the liquefied soil loses its shear strength and its ability to support foundation loads (Figure 3.11)

Figure 3.10: Photographs showing the extent of liquefaction, taken after the February 22nd earthquake around the suburbs surrounding the Avon River (Source: Diane Dixey, 2011)

Compared to ground shaking, landslides and tsunami hazards, liquefaction is less likely to cause conventional collapse of buildings and fatalities. Liquefaction induced building damage typically includes foundation settlement, tilting and or displacement due to lateral spreading, foundation settlement occurs either where soils beneath the building has settled due to volume change or where the strength of soils has decreased causing the structure to sink into the ground (Bird and Bommer, 2004).

Damage from liquefaction induced lateral spreading is usually more extensive than from liquefaction settlement. The magnitude of lateral spreading movement is much greater when ground shaking is more intense. Lateral spreading has been found to occur predominantly in river areas with alluvial and deltaic deposits including old and existing river channels. Liquefaction predominantly occurs around estuarine and coastal areas and in particular areas comprised of reclaimed soils or poorly compacted man-made fill (Bird and Bommer, 2004). This means that areas along river banks and estuaries are particularly susceptible to earthquake induced liquefaction and lateral spreading.

Figure 3.11: Photographs showing the floatation of buried structures and the tilting of homes due to liquefaction (Source: Diane Dixey, 2011)

3.5 The Darfield Earthquake September 4th 2010

The Darfield earthquake struck the South Island of New Zealand, roughly 30 km west of Christchurch City and near the town of Darfield on the 4th of September at 4:35 am (Wood *et al.* 2010 and Wotherspoon *et al.* 2012) (Figure 3.13). The Darfield earthquake's epicentre was located at 43.55°S, 172.18°E and was a moment magnitude (Mw) 7.1, at a depth of 10 km and is the first large earthquake to strike near an urban city in New Zealand since the Mw 8.3 Hawkes Bay earthquake of 1931. As discussed previously, prior to the Darfield earthquake the Canterbury Plains had historically been an area of relatively low seismicity for the New Zealand region and no active faults had previously been mapped in the immediate Christchurch region (Pettinga *et al.* 2001; Kaiser *et al.* 2011). Fortunately this quake caused no fatalities and only two serious injuries, this was impart due to the timing of the earthquake being in the early hours of Saturday morning when people are not in the streets or the CBD and in combination with the strong performance of the houses and business buildings.

The emergency response following the earthquake was efficient and effective, due to the preparedness and appropriateness of emergency planning across local authorities, life lines utility operators, engineers and national authorities. A local Emergency was declared under the Civil Defence Emergency Management Act 2002 by both the Christchurch City Council and the Waimakariri and Selwyn District Councils. The earthquake and its aftershocks were recorded and reported by GeoNet, the principal geological hazard monitoring system for New Zealand which provided efficient information to the media and the public. The aftershock sequence that followed the Darfield earthquake up until the November 28th 2010 included 135 earthquakes of greater than Mw 4 and 13 of these were greater than Mw 5 (Wood *et al.* 2010).

Scientists from the University of Canterbury and GNS mobilised immediately after the quake and within five hours had identified the surface fault rupture. The main shock is complex, comprising of four rupture sources identified in close proximity in time and space. The 30 km long surface rupture (Figure 3.12; 3.13) was observed on a previously unidentified fault now known as the Greendale Fault (Kaiser *et al.* 2011 and Wood *et al.* 2010). Because the Canterbury Plains are covered by alluvial gravels, previous faults have been hidden from geo-scientists and it is believed that the newly found Greendale fault was pre-existing and a part of it was re-activated during the Darfield earthquake (GeoNet, 2012).

Figure 3.12: Image of the Greendale fault rupture running through a road (Source: GNS Science, 2012)

The observed surface rupture is along a east-west tracing fault line from about 4 km west of Greendale (in the west) and about 2 km north of Rolleston (in the east). The western most end of the fault (about 5 km) approximately follows the course of the Hororata River and in one place partially blocks the river channel which lead to minor flooding of the adjacent fields. Along the Greendale fault, rupturing had produced clear, right-lateral displacements to roads, fences, shelter belts and other linear features (Elliot *et al.* 2012). A major feature of the surface fault rupture was the large dextral (right-lateral) displacement, the largest displacement was 5 m in the central portion of the fault and the average displacement was 2.5 m over the entire length of the fault. The maximum vertical displacement was about 1.5 m but generally 0.75 m along the length of the rupture. Overall the mapped length of the surface rupture associated with the Darfield earthquake along the Greendale Fault suggests that the rupture of this fault accounted for the main seismic moment release of energy during the earthquake (Holden *et al.* 2011).

Ground motions in Christchurch city during the Darfield earthquake ranged from horizontal accelerations of 0.3 *g* in the city centre and averaged 0.6 *g* city wide. One record located close to the Greendale fault had a peak vertical acceleration of 1.26 *g* (Wood *et al.* 2010). Peak ground accelerations were spatially variable between recorded sites over the Christchurch region due to complex near surface geology (Kaiser *et al.* 2011). Wood et al 2010 noted that there was a marked difference in the records on sites of deep alluvium and those on shallow stiff soils. In particular, there was a localised 5 km-wide area of high amplification ground shaking in the northern parts of the city and in the small basin in

Heathcote Valley and at the edges of the Port Hills. It has been argued that the most significant aspects of the Darfield earthquake were geotechnical in nature, with liquefaction and lateral spreading the main cause of damage (Wood *et al.* 2010).

3.5.1 Performance of Buildings and Lifelines

Modern buildings and lifelines generally responded adequately during the Darfield earthquake. However the recorded strong ground motions indicate that for most, the shaking was below New Zealand earthquake building design standards. Extensive areas of liquefaction and lateral spreading caused damage to residential and commercial properties and to lifelines in areas particularly close to topographical lows including stream channels, rivers, wetlands and coastlines. Major impacts to building were related to unreinforced masonry buildings (URM) which are made of clay bricks and damage was extensive to brick chimneys and fences. Fortunately only two unoccupied, unreinforced masonry buildings completely collapsed after an Mw 5.1 aftershock occurred less than 5 km away from them. URM buildings in the Christchurch and Kaiapoi Township suffered partial collapse due to strong ground shaking while modern structures in the same areas were unaffected. Lifelines were also affected as a result of the earthquake with damage to 13 bridges (Polermo *et al.* 2011) there was also a loss of power and water supply, but 90% of power was restored within 24 hours, and water supplies were mostly restored within 5 days (Wood *et al.* 2010). The Christchurch city trunk and main pipe lines were damaged at 305 locations and the sub main pipelines reported repairs at 400 locations following the Darfield earthquake (Milashuk and Crane, 2012).

The seismic shaking resulted in extensive ground liquefaction and lateral spreading in localised areas of Christchurch and outlying suburbs including Kaiapoi and Brooklands. Observations indicated that the most extensive damage to residential buildings was due to ground damage as a result of liquefaction and lateral spreading. Land damage mapping prepared by Tonkin and Taylor in the weeks following the earthquake indicated that the following areas were most affected by land damage;

- Riverside areas, particularly in the bends and in historic river channels including Avondale, Avonside, Burwood, Dallington, Kaiapoi, Fendalton and Halswell.
- River delta and lagoon areas, including Bexley, Brooklands, Kairaki, Pines beach, Redcliffs, South shore and Spencerville.

- Inland loose alluvial deposit areas, including Belfast, Bishopdale, Casebrook, Parklands, Richmond and Saint Albans,

The river areas experienced lateral spreading towards the streams and rivers causing cracking, deformation and differential settlements of buildings and pipe networks and inundation of land and buildings with sand and water. In the river delta and lagoon areas there was a mix of lateral spreading, ground oscillation and liquefaction related settlement, which resulted in damage and inundation of buildings and pipelines. The inland loose alluvial deposit areas had damage that was a result of ground oscillation and the ejection of sand and water and liquefaction-related settlement, this resulted in minor and localised damage to buildings and pipelines (Jacka and Murahidy, 2011).

As a result of the Darfield earthquake some 3000 houses had to be rebuilt or needed to be weather proofed. The most common type of damage for older houses was chimney collapses and around 26,000 chimneys are claimed to have collapsed as a result of the earthquake. Falling chimneys resulted in the damaging of roofing structures, neighbouring properties and vehicles but fortunately no loss of life. The performance of houses found on lateral spreads was inadequate particularly houses with light wooden frames, built upon concrete slabs, which had no provision for foundations on potentially liquefiable soils or lateral spreads.

Because so many residential properties were affected by earthquake shaking and many by lateral spreading and liquefaction, the investigation of land damage and remediation options became a priority recovery activity managed by the Earthquake Commission (EQC) (Wood *et al.* 2010). Tonkin and Taylor co-ordinated a team of geotechnical engineers and engineering geologists to undertake detailed assessments of land damage at properties in the most affected regions. At the conclusion of the land damage mapping assessments a total of 39,000 properties had been mapped by December 2010. 22,000 were classified as having no land damage and of the remaining 17,000 mapped properties, 9% had very severe or major land damage, 52% had moderate land damage and 39% had minor land damage. The EQC received 157,000 insurance claims for the September 4th earthquake and in 24,000 of these EQC claims the claimant indicated that land damage had occurred (Jacka and Murahidy, 2011).

3.6 The Christchurch Earthquake February 22nd 2011

In comparison to the Darfield earthquake the Christchurch earthquake that struck 5 months later on the 22nd February 2011 at 12:51pm had devastating and widespread impacts on Christchurch City and surrounding communities. The moment magnitude 6.3 earthquake struck almost directly below Christchurch at location 43.60^0 S, 172.71^0 E, only 6 km south-east of the CBD, at a shallow depth of 5 km (Figure 5.13). It struck in the middle of the working day, causing extreme ground accelerations which created extreme ground shaking over the region (Kaiser *et al.* 2012 and Hancox *et al.* 2011).

A rich set of strong ground motion shaking records were captured in this earthquake by the EQC-GNS GeoNet Seismic Hazard Monitoring network, which has more than 50 seismic instrumentation stations located within 100 km of the Christchurch CBD (Yuen Kam and Pampanin, 2011). The impacts of this earthquake were severe, causing an unparalleled level of damage in New Zealand's history and the largest number of casualties since the 1931 Napier earthquake (Curbrinovski *et al.* 2011). The collapse of several inner city office blocks and old unreinforced masonry buildings contributed to the deaths of 182 people.

Liquefaction was wide spread with lateral spreading, flooding, and subsidence primarily affecting the eastern suburbs of the city and the severity of strong motion shaking also resulted in significant rock-falls in the suburbs on and surrounding Port Hills. The effects of the Christchurch earthquake were devastating. Rock-falls and slope failures impacted hillside areas of Lyttleton, Sumner, Redcliffs and along the Summit road east of Dyers Pass and liquefaction and lateral spreading impacted the CBD and eastern suburbs rendering several hundred properties and residences unsafe (Hancox *et al.* 2011). In total it is estimated that 900 buildings in the central business district and 10,000 residential may have to be demolished with total repairs estimated to cost NZ$15-30 billion, making this event the most costly in New Zealand's history (Stevenson *et al* 2011).

Overall the defining features of the February 22nd earthquake was the severity and spatial extent of liquefaction and the near record breaking, severity of ground motion shaking (Curbrinovski *et al.* 2011 and Kaiser *et al.* 2012). Seismologically, this earthquake is classed as an aftershock of the Darfield earthquake due to its relationship to the ongoing activity since September 2010, where over 4000 aftershocks were recorded over the Greendale Fault.

Geo scientists knew that the occurrence of a large aftershock following the Darfield event was statistically possible, but the long time interval and decrease in seismic activity made the February event less likely to happen, but unfortunately it did. It is known that earthquakes interact, research in the last decade demonstrated that over major faults where earthquakes have been registered, the probability of occurrence of a second earthquake increases or decreases according to stress changes. The hypothesis of these studies state that once an earthquake occurs, the stress does not dissipate but propagates into the surrounding area, where it may increase the probability of another earthquake (Stramondo *et al.* 2011).

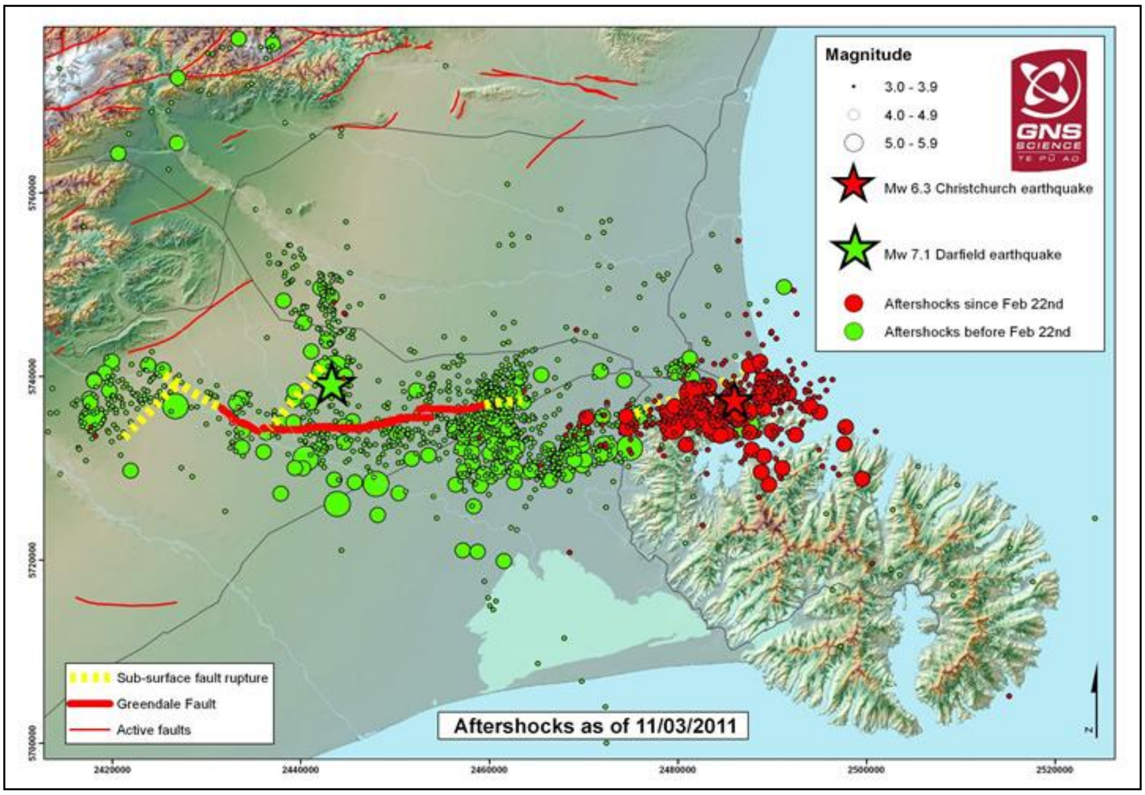


Figure 3.13: Map showing the location of the two main earthquake events and their subsequent aftershocks (Source: GNS Science, 2012)

The Christchurch earthquake occurred on the eastern fringe of the Greendale fault aftershock zone on a previously unmapped northeast-southwest- striking fault that did not rupture the surface. Several strong aftershocks of >Mw 5 followed the February earthquake including a Mw 6.0 event on June 13th 2011 and Mw 5.8 and Mw 6.0 on the December 23rd 2011 (Figure 3.14). Globally there have many earthquakes that have occurred with a similar magnitude of the Christchurch earthquake. However, the Christchurch earthquake had notably extreme high peak ground accelerations (PGA) with records showing 2.2 *g* (vertical) and 1.7 *g* (horizontal) at Heathcote Valley, 2 km from the epicentre and PGA recorded within the CBD ranged from 0.6 *g* to 0.8 *g* (Baird *et al.* 2011). Vertical accelerations were particularly strong and rich in high frequency energy and were the highest ever recorded in New Zealand and among the highest recorded in the world (Kaiser *et al.* 2012).

The other distinctive feature of the Christchurch earthquake as well as the strong peak ground accelerations was the severity and spatial extent of liquefaction and lateral spreading in the CBD and in the eastern suburbs. As previously noted the near surface geology of Christchurch is dominated by river and coastal processes and as such has highly variable soil profiles and properties which are important when concerning liquefaction potential.

As discussed previously, an important feature of Christchurch's geology is the high water table, with a depth of 1m or less below the surface in the east of the city with exception to areas close to the Port Hills. The depth of the Riccarton gravel layer (the upmost aquifer beneath the city) increases in depth towards the eastern part of the city. The Springston formation (alluvial gravels, sands and silts) is the dominant surface layer in the western part of Christchurch and the Christchurch formation (swamp, estuarine, lagoon, dune and beach deposits) is the dominant surface feature in eastern Christchurch.

Table 3.2: Table showing the magnitude and peak ground accelerations of the three largest earthquakes in the Canterbury sequence

Event	Magnitude	Peak Ground Acceleration (G) Maximum Horizontal	Peak Ground Acceleration (G) Maximum Vertical
Darfield, September 4th 2010	7.1	0.8	1.3
Christchurch, February 22nd 2011	6.2	1.7	2.2
Sumner, June 13th 2011	6.0	2.0	1.1

Consequently it can be argued that significant liquefaction observed in the eastern suburbs of the city and the absence of liquefaction in the west can be attributed to three factors: 1) a reduction in the amplitude of ground shaking moving from east to west 2) a gradual change in surficial soil characteristics 3) an increase in water table depth from east to west (Cubrinovski *et al.* 2011). The suburbs most effected by liquefaction during the Christchurch earthquake was along the meandering loops of Avon River to the east and north east of the CBD including Avonside, Dallington, Avondale, Burwood and Bexley, the soils in these areas are predominantly loose river deposits of liquefiable clean and fine silts and sands.

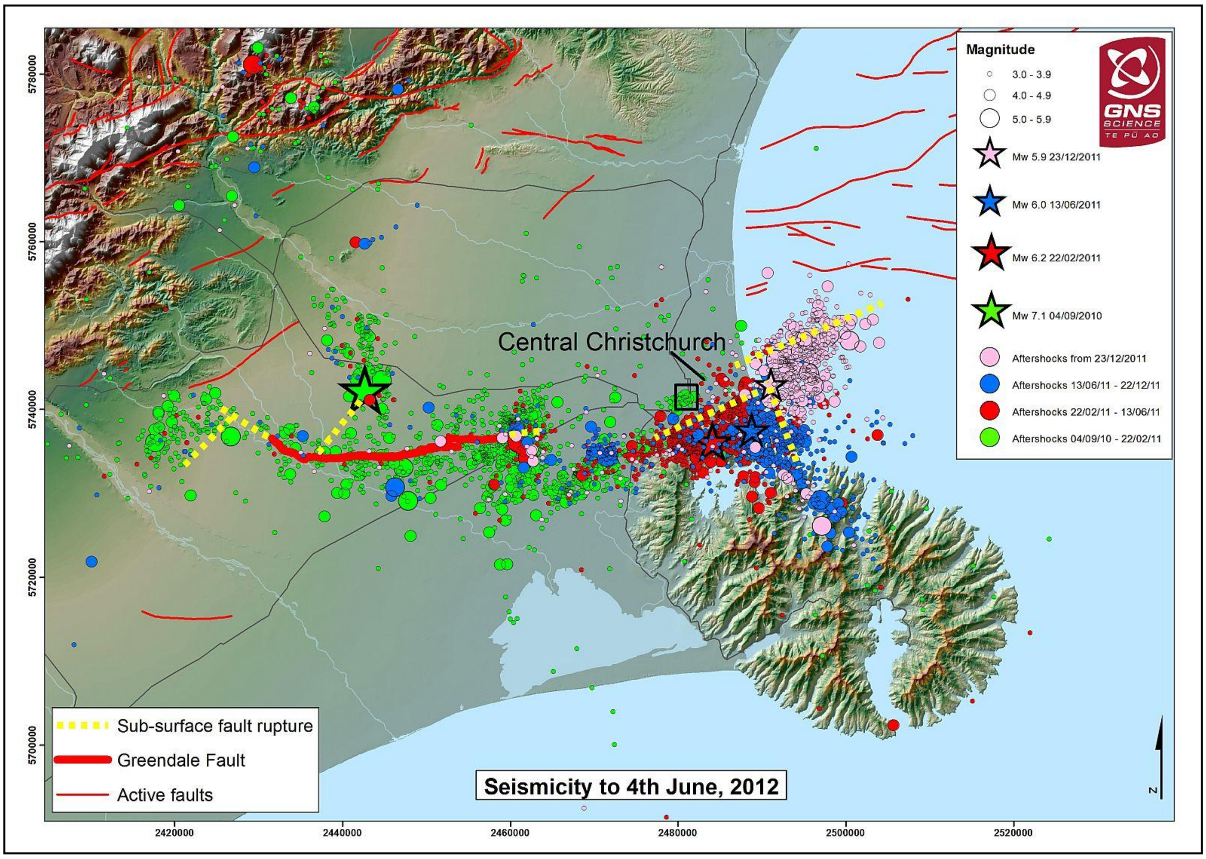


Figure 3.14: Map showing the location of the June earthquake (blue) and December earthquake (pink) (Source: GNS Science, 2012)

The more extensive liquefaction observed in these areas during the Christchurch earthquake is consistent with the fact that the seismic demand specific to liquefaction was about 1.5-2.0 times greater in the Christchurch event compared to the Darfield event. The south west of the city (Halswell) was the exception as there was more extensive liquefaction observed during the Darfield event as seismic demand was higher in this area (Kaiser *et al.* 2012). In areas close to water ways the liquefaction was often accompanied by lateral spreading, causing severe and extensive damage to properties and lifelines. Christchurch has approximately 150,000 dwellings and around 20,000 of these were seriously affected by liquefaction and of these nearly 6000 residential properties were abandoned in the “red zone” in 2011 along the Avon River because damage is beyond economic repair (Cubrinvoski, Henderson and Bradley, 2011).

3.6.1 Performance of Buildings and Lifelines:

During the Christchurch earthquake there was widespread and severe damage to buildings and lifelines. In particular there was significant damage to unreinforced masonry buildings (URM) in the CBD and the eastern suburbs (Figure 3.15). The aftershock effects of the Christchurch event was 4 -6 times greater than the Darfield event, the Darfield event resulted in loadings that were two thirds of the design level of new buildings and the Christchurch event resulted in 3 times the loading of the Darfield event. URM buildings were required by legislation to be strengthened to 33% of new building standards and in some cases owners reinforced their URM buildings to 100%, the latter being a rare case. Thus those URM buildings that were only strengthened to 33% of design standards experienced loadings 6 times greater than what they were strengthened for during the Christchurch earthquake. During the Christchurch event lateral accelerations had a strong east-west orientation causing URM building failures, primarily due to connection failures in the north-south walls, while east-west wall failures exhibited shear wall cracking and overall 50% of URM buildings were severely damaged due to the failure of connections (Ingham *et al.* 2011).

As well as URM buildings experiences severe damage, reinforced concrete buildings (RC) also experienced significant effects. There were 833 buildings within the CBD with reinforced concrete systems and 16.2% of these were severely damaged. Of the 182 fatalities, 135 were caused by the complete collapse of two medium rise RC buildings. In general it can be noted that the seismic shaking experienced in Christchurch significantly exceeded the 500-year design standard expected for design levels of new buildings in New Zealand.

Christchurch's CBD had approximately 3000 buildings which consisted of predominantly commercial and light industrial buildings (58%) and residential buildings made up the other 42%, with one or two storey buildings making up the majority of the CBD (82%). 127 buildings had at least six storeys and the tallest building was the Grand Chancellor Hotel with a total of 22 storeys. Liquefaction ground damage induced differential settlement of buildings, resulting in foundation damage and permanent tilting of the building. Buildings with pile foundations generally exhibited less differential settlement and liquefaction induced tilting compared to high rise buildings on shallow foundations on liquefiable soils which generally exhibited substantial settlement and tilting (Yeun Kam and Pampanin, 2012). In March of 2011 3000 buildings had been inspected and 23% were tagged as red (i.e. un-safe =

no entry permitted) and 53% were tagged as green (i.e. safe = entry permitted) (see Table 3.3 and Figure 3.16).

Figure 3.15: Photographs showing the collapse of homes and large unreinforced masonry buildings (Source: Diane Dixey, 2011)

As well as buildings being subjected to earthquake damage lifeline networks were also severely impacted. Lifelines are utility and transport services that include roads, telecommunications and power, water and wastewater networks and when these lifelines are damaged the community is significantly impacted. Bridges form an integral component to the Christchurch transport network and utility network as bridges generally contain essential utility pipelines as well as forming part of the road network. The region within Christchurch and the surrounding Waimakariri and Selwyn districts have 800 road, rail and pedestrian bridges with 55% of these made up of reinforced concrete structures.

Within Christchurch the damage to bridges has been confined to the CBD and eastern suburbs with liquefaction induced lateral spreading affecting the bridges along the Avon and Heathcote rivers. Very few bridges sustained damage on non-liquefiable soils. Peak ground accelerations were much higher than the design level of most New Zealand road and highway bridges and as a result approximately 50 bridges were significantly damaged in the Christchurch earthquake. Fortunately there was no structural bridge collapses but there was significant damage induced by liquefaction and lateral spreading which caused the rotation of bridge abutments and damage to superstructures and utility pipelines underneath the bridges (Polermo *et al.* 2011).

Table 3.3: Table providing a definition of the stickers that were placed on building after being inspected for earthquake damage

Building Sticker Colour	Sticker Colour Definition
Red	Unsafe - do not enter or occupy
Yellow	Restricted use - no entry except on essential business. No public entry or residential occupation
Green	Safe - no restriction on use or occupancy

The spatial variability of damage to utility pipelines was a result of spatially variable seismic motion including both ground acceleration and velocity. Pipelines have a high probability of damage and exposure during earthquakes due to permanent ground displacement from fault offsets, liquefaction and landslides, which is why the Christchurch earthquake resulted in severe damage to utility pipelines. The Christchurch city trunk and main lines were damaged at 1436 locations and the sub main pipeline systems reported approximately 2000 repair locations following the Christchurch earthquake (Milashuk and Crane, 2012). Because the pipeline networks were damaged during the February earthquake, the associated effects on river and coastal environments included the discharge of raw sewage to rivers, beaches and the estuary, consequently creating a 12 month ban on all recreational activities within the waterways of Christchurch and the adjacent Pegasus Bay area.

Thousands of residential houses were significantly impacted by the Christchurch earthquake either by liquefaction induced lateral spreading and flooding or by landslides and rock falls (Figure 3.17). The liquefaction induced by this event was more widespread than in

September’s event causing damage to new areas and causing further subsidence of houses already damaged from the September quake.

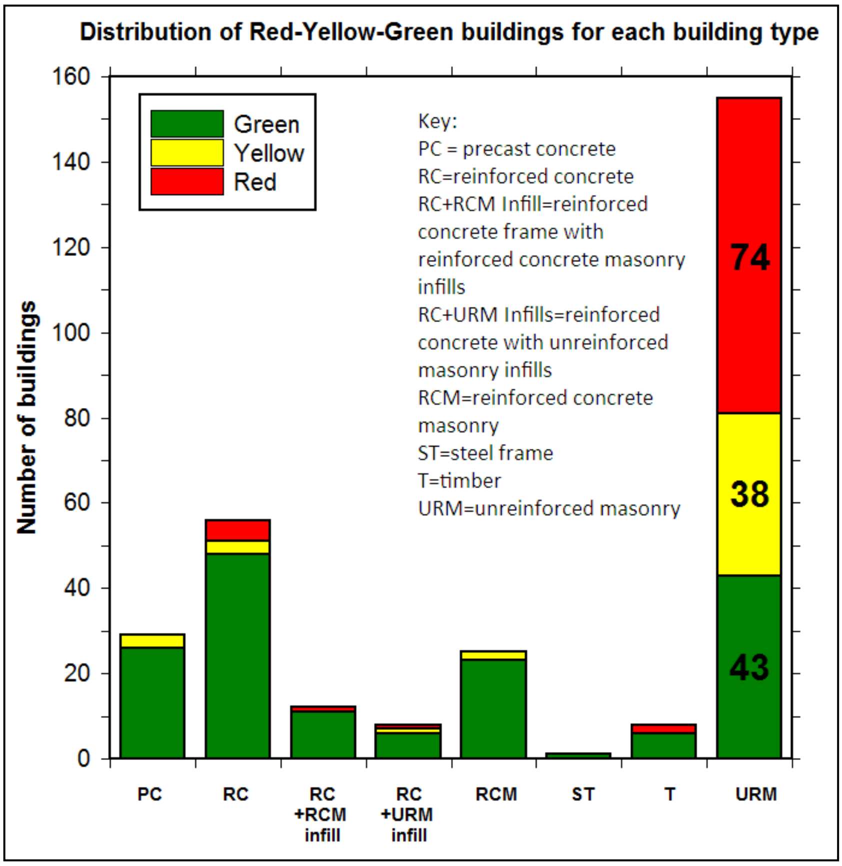


Table 3.4: Graph showing the number and type of buildings tagged red, yellow or green as a result of the Christchurch earthquake (Source: Ingham et al. 2011: 5)

Landslides and boulders broke away from the hillside areas surrounding the Port Hills causing the most significant damage to homes. Overall light timber framed houses generally performed well under the earthquake stress and severe damage of these buildings was not as a result of collapse but more to damage to facades including doors, windows, walls, ceilings and the rupturing of concrete floor slabs due to lateral spreading of foundations. URM houses and double brick houses did not perform well during the earthquake with homes resulting in collapse of exterior walls and roofs (Buchanan, *et al.* 2011). Overall 7,256 residences have been red zoned as at May, 2012; these residences are in the areas of Kaiapoi, Kairaki, Brooklands, Burwood, Avonside, Avondale, Bexley and Southshore (CERA, 2012).

Figure 3.16: Top photos show liquefaction and flooding in eastern suburbs and the bottom row shows damage to homes, note that damage is suffered to both older and new homes (Source: Diane Dixey, 2011)

3.7 Summary

This chapter detailed the geomorphological environment of Christchurch city and the wider environment of the Canterbury Plains including its geology, hydrology, tectonic setting and seismic history. This was presented in order to provide a context for the occurrence of the Canterbury earthquakes of 2010 and 2011 and the subsequent effects of the earthquakes on coastal and river environments within Christchurch and Canterbury. Canterbury is a region rich in significant geomorphological features, including the Southern Alps which is a vast mountainous ridge stretching the length of the South Island, resulting from the collision of the Pacific and Australian tectonic plates. Large braided river with high sediment loads are a significant feature cutting across the Canterbury Plains, including the Waimakariri River north of Christchurch city and the Rakaia River south of Christchurch city. These rivers have laid down alluvial sediments over the last 10,000 years resulting in deep alluvial fans which make up the majority of Canterbury's geology. These alluvial fans resulted in the masking of the historic seismic activity that underlies Canterbury, thus making the assessment of seismic hazards directly within Christchurch minimal and to some extent underestimated.

Christchurch city is dominated by coastal and river environments, as well as the large braided river surrounding the city's landscape Christchurch has 4 main spring-fed rivers running through and surrounding the CBD including the Styx, Avon, Heathcote and Halswell rivers. The Heathcote and Avon river mouths empty into the Avon Heathcote estuary, which is a large tidal estuary located on the eastern fridges of Christchurch city and enclosed by the large Brighton spit. Christchurch is a coastal city located along the Pegasus Bay coastline and is also boarded by Banks Peninsula which is an ancient volcanic area. Many suburbs are located along the banks of these rivers and around the narrow stretch of coastal land between the Port Hills of Banks Peninsula and Pegasus Bay, and along the Brighton Spit and the Estuary. Within Banks Peninsula on the southern side of the Port Hills are Lyttelton Harbour and the suburb of Lyttelton which holds the main shipping Port of the South Island. Thus Christchurch is a city where a majority of its suburbs are located within the plains and banks of rivers and the margin of the coast line and are hence subjected to the soil profiles that highly susceptible to liquefaction, lateral spreading and landslides.

The soils beneath eastern Christchurch are made up of fine sands, silts and peats formed around 10,000 years ago when eastern Christchurch was submerged by the Pacific Ocean during the last glacial melt. Eastern Christchurch is also subjected to a very high water table which is usually no more than 1m below the surface. Consequently the suburbs in coastal and river areas suffered the most significant impacts when the Canterbury earthquakes struck in both September 2010 and February 2011. The eastern suburbs were subjected to widespread liquefaction and lateral spreading which occurred because the sediments are fine and unconsolidated and the water table is also high.

Liquefaction, liquefaction induced lateral spreading, rock falls and landslides caused damage to land, commercial and residential properties, heritage buildings, infrastructure and essential lifelines. The associated effects on river and coastal environments included the discharge of raw sewage to rivers, beaches and the estuary, because the pipeline networks were damaged by the February earthquake; consequently there was a 12 month ban on all recreational activities within the waterways of Christchurch and the adjacent Pegasus Bay area. This study will seek to further understand and explain the effects of seismic activity on coastal and river environments and try to show that coasts and rivers play as significant a role as seismic, engineering and socio-economic factors in determining the impacts and recovery patterns of earthquakes.

4 CHAPTER FOUR: RESULTS AND DISCUSSION COASTAL AND RIVER VULNERABILITY: PAST AND POST THE CANTERBURY EARTHQUAKE SEQUENCE

4.1 Introduction

The results and discussions of this thesis consist of two separate chapters. Each chapter presents and discusses the findings from the analysis of the expert interviews and key information is supported with a figure derived from either photos or maps. The results and discussion in this chapter will present the interview results, which centre on the themes of coastal and river environments and the effects of the Canterbury earthquake sequence. Chapter Five will present the themes that centre on the current progress and patters of recovery, following the earthquake sequence.

This chapter deals with understanding the coastal and river environments within Christchurch and deriving how these environments may have influenced the effects of the earthquake sequence within and around the city. The research questions that lead the discussions in this chapter have been introduced in Chapter Two. These questions deal with coastal and river environments in Christchurch and aim to determine whether or not, they are more vulnerable to earthquake associated hazards such as liquefaction and lateral spreading. The questions also deal with whether or not earthquakes within coastal and river environments cause significant changes to other types of natural hazards that previously existed there. The following questions lead the discussion of the interview data for this chapter:

1. Are there specific natural features of past and present coastal and river environments that make them more vulnerable to earthquake induced hazards?
2. What were the effects of the Canterbury earthquake sequence on coastal and river environments and the built environment in Christchurch?
3. Has the Christchurch earthquake sequence influenced coastal and river environmental processes and future hazards?

This chapter starts by presenting the first themes found within the interview results. These first themes look at Christchurch's coastal and river history and the current coastal and river landforms and features found within Christchurch today. The following themes focus on the pre-existing natural conditions of Christchurch including present soils and sediments, the ground water table and topography of the area. The next part of the chapter focuses on the effects on the earthquakes on Christchurch, including the effects on existing coastal and river hazards. Understanding these themes is important as they link together to form an overall understanding of what conditions and processes are needed within an environment to generate earthquake associated hazards and how earthquakes can impact changes on other environmental hazards. A discussion on coastal and river vulnerability to seismic hazards and framing it within a management discourse is offered at the end of this chapter.

A key issue addressed in this chapter is why developing within coastal and riverside environments can be problematic especially in terms of multiple hazards. Coastal and river environments are prone to a number of natural hazards and some are more obvious than others. Development within these areas without a full awareness and understanding of the potential hazards has major implications for the safety of people and infrastructure that reside there. It is a combination of economic interest and lack of community awareness that leads to natural hazards such as earthquakes in coastal and river areas to be underestimated and lead to devastating disasters.

4.2 Coasts and Rivers

The Canterbury earthquake sequence has been the most destructive earthquake to impact New Zealand since the 1931 Hawkes Bay earthquake (Kaiser *et al.* 2012). Total repairs are estimated to cost NZ $15 to $20 billion with around 700 buildings in the CBD and around 7000 residential buildings already demolished or destined for demolition (CERA, June 2012). As presented in Chapter Three, the main areas of inner and surrounding Christchurch that were severely impacted by the earthquakes were areas surrounding rivers, coastlines and cliffs. Christchurch city is an area that is highly influenced by its geomorphic setting particularly its coastal and river setting. As such, the two main environments that were a focus of discussion during the interviews were coasts and rivers. This section will highlight the coastal and river setting of Christchurch including its history and present day setting, through information provided from the experts, photos, maps and literature. This section will then lead into the impacts of the earthquakes on Christchurch, towards the aim of establishing whether coasts and rivers have been more impacted by the earthquakes than other areas. It will present evidence from the expert interviews, maps and photos and relate this evidence back to literature and the hypothesis of this research.

‘Impact’ and ‘damage’, terms used frequently in this section, are terms that describe what effect the earthquake had on both natural and manmade environments. For the sake of this study ‘impact’ or ‘damage’ is anything from small scale cracks in buildings to large scale land slumping and building collapses, elaborations on the scale of these terms will be made when necessary.

Coasts and rivers were main themes discussed during the interviews. When experts were asked about where earthquake impacts occurred and why the impacts there were so significant, coasts and rivers was the main topic of concern. This theme highlights the coastal history of Christchurch as well as the history of rivers within the area. The ‘coast and river’ theme overall encompasses the coastal and river history of Christchurch and the impacts of the earthquakes on coastal and river areas. The coastal history of Christchurch in terms of historic sea level rise and river gravel deposits was one reason given for why impacts in the eastern suburbs were so severe due to liquefaction.

“A good half of Christchurch is built on surfaces that post date the last post glacial rise in sea level. We have in Christchurch a classic transgressive regressive sequence of shoreline movement where sea level once reached an elevation roughly around Deans Bush 7000 years ago. It is this area that has been most affected, if you go west of that post glacial sea limit except for small pockets around rivers and streams, it is very much less damaged” (Professor Emeritus R.M. Kirk – 9/8/2012).

“Western Christchurch is built on gravel deposits of the Waimakariri River and eastern Christchurch is built on old coastal deposits of the Holocene. The coastal and estuarine and river environments are areas where liquefiable sediments are laid down and are areas closest to sea level which means the water tables are higher which means they are more vulnerable to liquefaction” (Dr. Murray Hicks – 23/8/2012).

“Essentially in Christchurch there is that fine sand and coarse silts that are particularly vulnerable. These have been laid down by past river channels as well as present river channels. At rivers you have the free surface of the banks that you can get lateral spreads going towards the rivers, so that is why things were worse around the eastern suburbs and particularly by the rivers” (Dr. Marion Irwin – 30/8/2012).

It is understood that during the Quaternary, geological processes and landscape evolution of the Canterbury region was influenced by global cycles of warmer (interglacial) and colder (glacial) climates. Glacial and interglacial cycles have caused large fluctuations in sea level, which influenced sedimentation in coastal and offshore areas (Forsyth *et al.* 2008). The Pegasus Bay coastline was inundated by post glacial sea level rise up to roughly the western side of Hagley Park (Figure 4.1). This inundation period laid down fine marine sediments of sands, silts and peats deposited by the existence of estuaries and shallow transgressing seas, during previous warmer periods (Wilson, 1976). About 6,000 years ago, the Canterbury coastline began to prograde, using continental shelf sands and long shore drift from the Waimakariri, back out towards its present location. Later, river sediments of gravel and silt built up progressively over this prograded coastal zone. Up to 12 km of swamps and sand dunes had developed over inland Christchurch, during this 4000 year period of coastal progradation (Shulmeister and Kirk, 1993).

"In between the paused stages of [shoreline] movement there were dune ridges and in between the pauses there were rivers moving in among the dunes ridges" (Professor Emeritus R.M. Kirk – 9/8/2012).

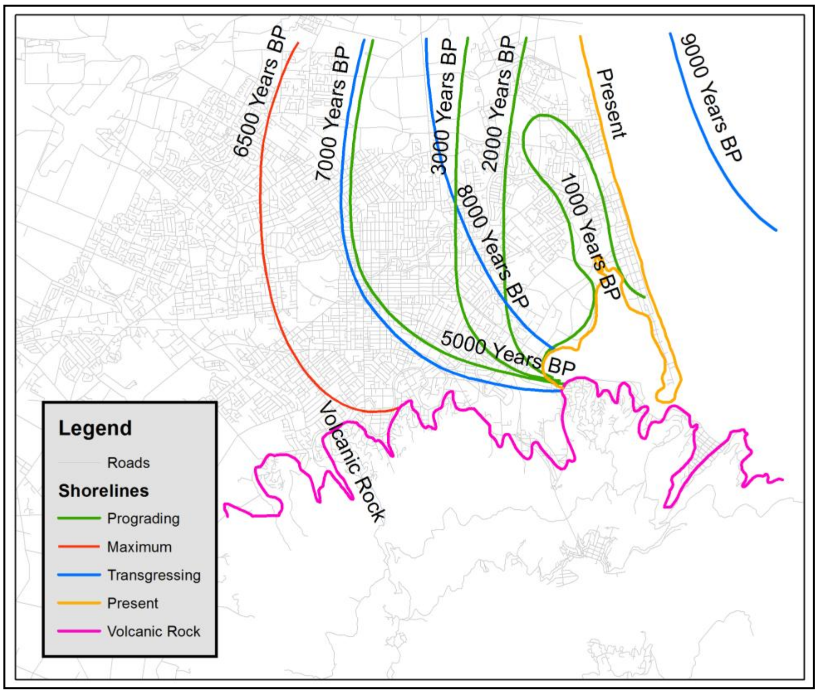


Figure 4.1: Map showing the movement of the Christchurch coastline over the past 9000 years, Figure adapted from Brown and Weeber, 1992.

As addressed in Chapter Three, the vast expanse of the Canterbury plains is comprised of floodplains and large gravel fans. Large parts of the plains are abandoned braided river channels that were last occupied during the last glacial maximum (Forsyth *et al.* 2008).

Fan building was controlled by fluctuations in river loading between climatic highs and lows during the Pleistocene as well as sea level fluctuations influencing river regimes and, possibly, by tectonic uplift in the Canterbury foothills. These processes all possibly played a part in the progressive eastward shift in river gravel fan apices (Wilson, 1976). The lowest shore line recorded in Canterbury was situated about 50 km seaward and 130 m lower than its present positions (Forsyth *et al.* 2008). Christchurch City itself has also been built upon past and present channels of a number of spring fed river channels (Figure 4.2).

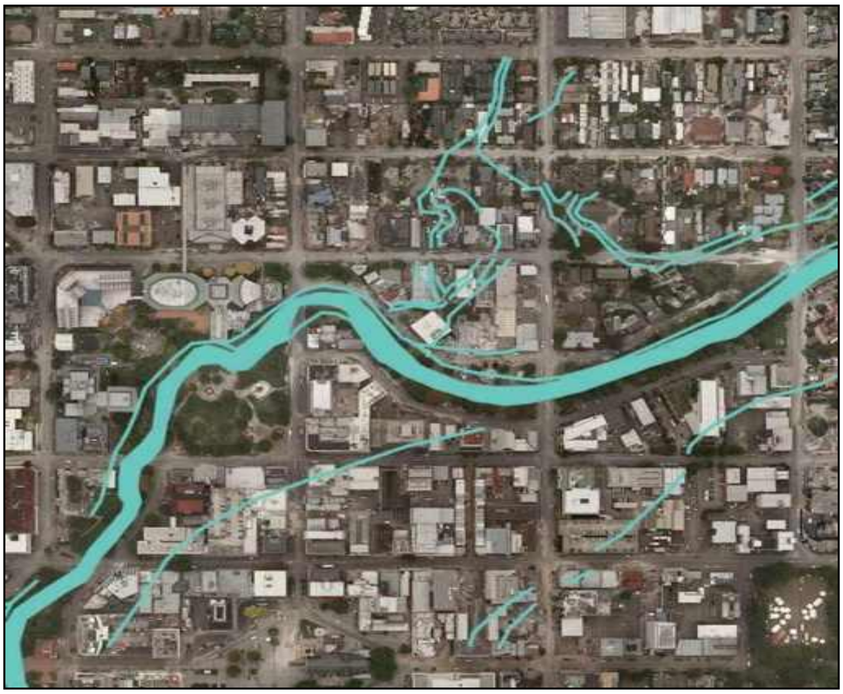


Figure 4.2: Past and present streams in central Christchurch as mapped in March 1850, superposed on aerial photography from 2011. Streams digitised from the Black Map of Christchurch, March 1850. (Source: Lucas Associates, 2011)

The city of Christchurch and the wider Canterbury region are built on foundations of interbedded terrestrial river gravels and fine-grained and estuarine sediments (Figure 4.3). The gravels contain high yielding aquifers and the interbedded finer sediments are essentially of low permeability which confines the water under pressure within the gravels. The interbedding of these sediment deposits form a discontinuous lens of interbedded material which results in significant variability in the sediment profile from one point to another. In general there is a sequence of alternating sand, silt, gravel, clay and sometimes peat beds and the proportion of gravel beds is expected to be higher in the west and decreases towards the east (Jacka and Murahidy, 2011).

The next few quotes indicate the damage that the experts observed or knew about, as a result of the earthquake sequence:

"Lots of coastal land around the lower Avon has sunk by more than 2 m in some places and Bexley has gone down by 1.3 m" (Professor Emeritus R.M. Kirk – 9/8/2012).

"After September it appeared that the [Waimakariri] river didn't suffer much damage but the ground surface around the area did suffer significantly after February there were more effects to the river. The river level rose up causing a jump in the hydrograph. Subsequent cross sectional surveys showed lots of slumping in river sides, and the river had also heaved up from the bottom. Cross section of the river had reduced significantly" (Dr. Graham Harrington – 30/8/2012).

"River and coasts are not more vulnerable to ground shaking or ground ruptures. But definitely more vulnerable to liquefaction because of low lying ground with high water tables and those products in Canterbury tend to be near rivers" (Dr. Marion Irwin – 30/8/2012).

"After the September quake, I found that most damage was along the Kaiapoi River" (Dr. Sonia Giovinazzi – 10/8/2012).

"In coastal areas where you have free surfaces like coastal cliffs and river banks where stuff can move sideways and you get shaking, they are going to be more vulnerable. Coastal cliffs are vulnerable because they have been standing there for thousands of years that have a lot of weathering and give it a good shaking there are going to be fractures that are going to fall down" (Dr. Marion Irwin – 30/8/2012).

As detailed in Chapter Three, between the periods of September 2010 and December 2011 the Christchurch region was struck by a series of earthquakes including six significant events: September 4th 2010 (Mw = 7.2), February 22nd 2011 (Mw = 6.2), June 13th 2011 (Mw = 5.3 and Mw = 6.0), and December 23rd 2011 (Mw = 5.8 and Mw = 5.9). The causative faults of these earthquakes were within, or very close in proximity to, Christchurch city, thus generating very strong ground motion shaking which caused tremendous damage throughout the city area (Cubrinovski *et al.* 2011).

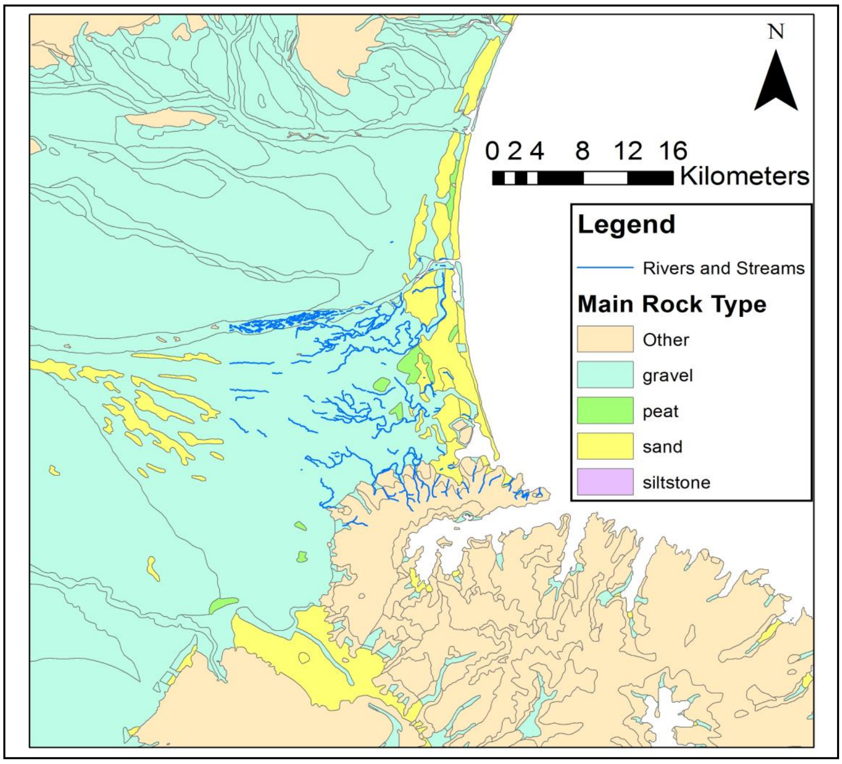


Figure 4.3: Map showing the main rock types found over the Canterbury region, gravels laid down by rivers, sand and silt laid down by previous marine environments and peats laid down by swamps.

Land damage as indicated by the experts above, was primarily around rivers and throughout the eastern suburbs, which is primarily built upon old coastal sediment deposits. Land damage mapping undertaken by Tonkin and Taylor indicated that land damage was predominant in riverside suburbs particularly the inside of historic river channel meander bends, this fact was also observed by expert Justin Cope below.

"Horse Shoe Lake, which is an old river channel got hammered in the September earthquake and every other subsequent earthquake after that in terms of liquefaction. This is because of the water table height and the sediments that are there" (Justin Cope – 30/8/2012).

The Greendale fault ripped through the Hororata River causing relatively localised effects on the river channel. Basically it down dropped a meander bend, the throw in fault was about 1.5 m which dropped the meander bend and the farmer that lived near the bend found that the river began to flow right by his house" (Dr. Murray Hicks – 23/8/2012).

Other areas of significant damage were around the river deltas and estuarine areas and areas of loose alluvial deposits. River deltas include those around the Avon Heathcote Estuary and Brooklands Lagoon (Kaiser *et al.* 2011). Near rivers, lagoons and estuaries, lateral spreading towards the water, caused most of the damage seen in residential areas. Lateral spreads result in the cracking and settlement of buildings, roads and pipe networks while liquefaction causes the inundation of land and buildings through the ejection of sand and water from the ground (Jacka and Murahidy, 2011).

"Because a lot of homes are located close to the [Avon] river they were also affected by lateral spreading, slumping and the ground levels lowering" (Dr. Graham Harrington – 30/8/2012).

Originally, the site of eastern Christchurch comprised of swamps, lying behind areas of sand dunes, estuaries and lagoons, while western Christchurch comprised of gravels, sand and silts from river channels and the flood plains of the Waimakariri River (Brown and Weeber, 1992).

"In the old coastal dune deposits particularly around the Travis Country road area which has 2-3000 year old dune deposits, the high bits had dune slacks that were wet. Subdivisions were built on these old dune slacks. You can kind of see that some houses were more affected by liquefaction, so I have a suspicion that liquefaction and subsidence coincided with where old dune slacks were. Even though the dunes had been removed, the sediments beneath them remain" (Justin Cope – 30/8/2012).

The geological history of Christchurch appears to have been a major player in the subsequent damage observed during the earthquake sequence, with damage patterned with areas surrounding rivers and old coastal sediment deposits. The observed patters of damage in Christchurch can also be observed in other earthquake events worldwide, including the 1886 Charleston earthquake, located on the coastline of the Atlantic Ocean in South Carolina, where the phenomenon of liquefaction was extensive around the epicentre and lateral spreading occurred along the Ashley River (Wong *et al.* 2005).

To close this section it can be concluded that the coastal and river history of Canterbury has played a significant role in the emergence of impacts associated with the Canterbury earthquake sequence and that present coastal and river environment have been significantly impacted by the earthquake events themselves. The history of sea level rise which inundated eastern Christchurch and subsequently laid down coastal and marine sediments was a contributing factor to the present day existence of liquefiable soils, which are predominantly found in the eastern suburbs. These liquefiable soils caused widespread liquefaction induced land damage across eastern Christchurch which resulted in damage to residential and commercial buildings, lifelines and infrastructure.

The history of river flooding across Christchurch was also a predominant factor that played into patterns of earthquake impacts because damage associated with lateral spreading and liquefaction followed that of old and present river channels. Liquefaction in the eastern areas and parts of western Christchurch was a result of loose alluvial gravel deposits laid down by past flooding events of the Waimakariri River and the present location of the spring fed streams including the Avon and Heathcote rivers were areas of most significant impacts as a result of both lateral spreading and liquefaction.

The ‘coast and river’ theme, supports the hypothesis of this research. The theme indicates that coasts and, rivers past and present, have played a significant role in determining spatial areas of damage as a result of the earthquake sequence. There is consensus among the experts regarding the theme as experts all agreed and advocated that damage during the earthquake was situated around rivers and within the eastern suburbs. The experts also agreed that it was the presence of liquefiable soils that were the main contributing factor for inducing these damages and that those soils were present because of either coastal or river processes.

4.3 Christchurch Geology and Hydrogeology

The experts interview responses also focussed on the themes of ‘geology’ and ‘hydrogeology’. When questioning the experts about the main driving factors of earthquake damage the words ‘soils’, ‘sediments’, ‘ground water’ and ‘water table’ were brought up frequently, so they were grouped together to form this ‘geology/hydrogeology’ theme. As explored in Chapter Three, the geology and hydrogeology in Christchurch seems to have been a significant contributing factor to the occurrence of liquefaction and liquefaction induced lateral spreading as a result of the two most significant earthquake events.

The ‘geology and hydrogeology’ theme will describe the types of soils and sediments that the Christchurch area is built upon and what the water table level is throughout the city. The theme aims to highlight how the soils and sediments under Christchurch together with the water table are the key ingredients for triggering liquefaction when a sizeable earthquake event occurs. This in turn will also cover why liquefaction was a more prevalent hazard in the eastern suburbs than it was in western Christchurch. The theme also highlights a flaw in the research hypothesis of this study, which will be discussed later in the section. These first few quotes from the experts give an understanding of what the sediments types are and what the water table is like beneath eastern Christchurch:

"A high proportion of these environments are comprised of very fine sands and silts. It is produced typically from greywacke and the most common manifestation of it is from the Port hills and is known as loess. And when it is re-worked by river channels and into sea beds and so on it becomes grey, muddy looking stuff. The combination of high water tables and fine sediments is tailor made for liquefaction to occur" (Professor Emeritus R.M. Kirk – 9/8/2012).

"But liquefaction was everywhere on the flat ground because of the high water table and liquefiable soils present. Liquefiable soils are present because the Avon and the Heathcote are the rivers that have laid down those particular sediments, silts. Low lying flat land, with high water tables and fine sediments from rivers are the fatal combination for liquefaction in the eastern suburbs" (Dr. Marion Irwin – 30/8/2012).

"Areas are vulnerable to liquefaction damage because of a combination of sediment type, high water tables and the proximity to rivers. The coastal and estuarine and river environments are areas where liquefiable sediments are laid down and are areas closest to sea level, which means the water tables are higher, which means they are more vulnerable to liquefaction" (Dr. Matthew Hughes – 6/8/2012).

"Areas are more likely to liquefy because the sediments are unconsolidated soft materials, sands and silts, with river gravels laid over top and the water table depth is high" (Shamus Wallace – 27/8/2012).

"You have got to have the right soil type for liquefaction. It has got to be unconsolidated, no cementing, with grains stacked on top of each other. It's got to be particular types of soils, any plasticity or clay content within the soil means the soil will never liquefy. Essentially in Christchurch there is that fine sand and coarse silts that are particularly vulnerable. These have been laid down by past river channels as well as present river channels" (Dr. Marion Irwin – 30/8/2012).

Liquefiable sediments have been characterised as those of fine grain size, unconsolidated and must consist of little to no clay material (Ambraseys and Sarma, 1969). As indicated by the Marion Irwin, these fine sands and sediments have little no clay content which means that they have little plasticity. Plasticity is observed in soils that lose and subsequently regain about 99% of their inherent shear resistance to sliding after they absorb or lose water, for example, clay will turn to sticky mud after the addition of water (Carter and Bentley, 1991).

The experts above indicate that it is the combination of fine grain sized sands and silts and high water tables that are responsible for the occurrence of liquefaction in the eastern suburbs. They note that this combination is located there because of past coastal and river processes. They used the phrases “the combination is tailor made for liquefaction” or “ it is a fatal combination for liquefaction and “areas are more vulnerable to liquefaction”, subsequently meaning that there is agreement among the experts, that the occurrence of these two features are the two most important ingredient for explaining the spatial occurrence of liquefaction during the Canterbury earthquakes. The third ingredient, ground acceleration, above the threshold, occurred over much wider areas than where liquefaction occurred, so is also a contributing factor but not a spatial determinant of liquefaction.

Although the experts agree on the ingredients needed for liquefaction, it does appear that there are differences in the way in which the experts believe that those ingredients got there. It appears that Marion Irwin attributes the existence of liquefiable soils down to past river processes combined with high water tables, whereas Justin Cope and R.M Kirk attribute them more to past coastal processes. As seen above, Marion quotes more on rivers while Justin and R.M quote more on coasts. This difference and subsequent differences can be attributed to an expert’s positionality, as discussed in Chapter Two, an expert’s positionality needs to be considered when interpreting expert responses to questions. The expert’s areas of expertise are different which can account for a diverse range of responses. In this case even though the responses are dissimilar, they are both correct, as it is a combination of both coastal and river processes that are responsible for the existence of liquefiable sediments. The following again highlights how these sediments came into existence.

As detailed in Chapter Three, fine grained sediments were laid down around 6500 years ago when sea level once reached its maximum in-land location and encompassed all of eastern Christchurch (Leckie, 2003) (Figure 4.1). This was during a time when the Pegasus Bay coastline was in a transgressive state which resulted from a low sediment supply when the Waimakariri River flowed to the south of Banks Peninsula, thereby cutting off sediment supply to Pegasus Bay (Basher *et al.* 1988). So at this point the existence of liquefiable sediments can be attributed to the transgressive movement of the coastline due to the lack of sediment supply from the Waimakariri River.

The Waimakariri subsequently avulsed and then flowed into what is currently known as the Avon Heathcote Estuary. Since this avulsion the Pegasus Bay coastline became progradational with an average rate of 0.6 to 2.8 my-1 with sediment supplied from the Waimakariri, Waipara and Ashley Rivers (Suggate 1958; Wilson, 1976; Shulmeister and Kirk, 1996). The progradational coastal plain of Pegasus Bay widens southwards from 200 m in the north to 6.6 km wide at the Avon Heathcote Estuary (Figure 3.3). This coastal plain consists of dune ridges, swamps, Aeolian dunes, abandoned river channels and estuaries (Leckie, 2003). The western edge of the coastal plain is the non marine Canterbury river gravels that have been deposited by the avulsion of the Rakaia, Waimakariri, Ashley and Waipara Rivers and forming the Canterbury alluvial fans. These coastal and river environments that make up this progradational plain are the reasons why fine sands and silts are found within eastern Christchurch.

Historical reports indicate that high water tables and marshy conditions were dominant features of the Pegasus Bay coastline prior to European settlement in 1850 (Leckie, 2003). Guy and Potter (1893; cited in Bowden 1986) write that “The site of the present city (Christchurch) was then a swamp, broken here and there by sandy ridges; a cold deep stream (Avon River) flowed through it, the flanks of which are covered with high flax and scrub....” Since European settlement the Christchurch areas had been drained of most of its surface water in order to make the land ready for the city’s development. Although people changed the surface water conditions of Christchurch they have not significantly changed the ground water conditions. The water table beneath Christchurch affects the upper 20 to 10 m of sediments and is generally 2 to 3 m below the surface to the west of the CBD and only 0 to 2 m below the surface in the CBD and eastern Christchurch (Jacka and Murahidy, 2011).

As addressed in Chapter Three, the water table is higher in eastern Christchurch (less than 1 m below the surface) because the area is closer to sea level and the water table is also higher around river edges (Figure 3.4). In order for liquefaction to occur, the water table depth has to only be 2 m below the surface, indicating that the entire eastern areas of Christchurch is vulnerable to liquefaction because of extremely high water tables.

“Areas closest to sea level, means the water tables are higher” (Dr. Matthew Hughes – 6/8/2012).

Where rivers are located is where there are high water levels because the river is located at the water table level” (Dr. Marion Irwin – 30/8/2012).

Liquefiable soils only occur among sediments that are below the water table level, the dry sediments above the water level will not liquefy (Obermeier, 1996). Because the water table is just below the surface in eastern Christchurch and around river banks, when a sizeable earthquakes happens, sediments close to the surface will liquefy causing significant land and infrastructure damage. Whereas in the west, because the water table is at a greater depth, because it is further from sea level, the potential for liquefaction during an earthquake will be significantly reduced.

The hypothesis in this study states that coasts and rivers are more vulnerable to seismic hazards. The following two quotes suggest that present day coastal environments are not so much more vulnerable to seismic hazards whereas river environments are, highlighting a possible flaw in the hypothesis.

"There is quite a contrast between what happened on the coast where there is a high energy compaction of sand compared with the areas behind the sand dunes where there is loose compaction of sand. The coastal areas haven't been drastically affected but river edges have been" (Dr. Graham Harrington – 30/8/2012).

"Liquefaction followed areas of flat land with unconsolidated sediments. Vulnerability to earthquake hazards is more to do with sediment type and depositional environment. New Brighton and Sumner are coastal areas but experience little to no liquefaction because the sediments have been continually worked by high energy wave processes that sorts the sediments into one grain size and consolidates the sediments which decreases the sediments susceptibility to liquefaction. (Shamus Wallace – 27/8/2012).

The above two quotes observed that liquefaction was not a prevalent phenomena in actual present coastal areas of Christchurch such as New Brighton and Sumner. This is because coastal environments are comprised of sediments that are more sorted, because they have been worked and compacted by wave processes which reduce the sediment's susceptibility to liquefaction. Both quotes observe that liquefaction was present throughout the breadth of the eastern suburbs and not just around rivers because of the unconsolidated and loosely packed sediments. This suggests that these two experts perceive that present day coastal zones are not more vulnerable to seismic hazards as they have not been impacted by liquefaction or lateral spreading, because of their sediment composition. However, this is in contradiction to the fact that lateral spreading and liquefaction did occur in areas surrounding the Avon Heathcote Estuary, which is considered as a coastal zone. In conclusion, it is the exposed coastline that is not as vulnerable to liquefaction or lateral spreading, however the exposed coastline is still vulnerable to earthquake events in other ways and this will be addressed in subsequent chapters.

The experts did agree that it is the type of sediments found in eastern Christchurch that are more vulnerable to liquefaction and the reason for why those sediments are located there is because of past coastal and river processes. Even though eastern Christchurch is not inherently a coastal zone further in land, it has been in the past. The previous section notes the significance of past coastal and river environments in Christchurch in determining where earthquake impacts were observed. This concludes that past coastal and river environments have made eastern Christchurch more vulnerable to liquefaction and lateral spreading during earthquake events.

To close this section it can be concluded that it is the geology and hydrogeology of an area, in conjunction with seismic events that determines the occurrence of liquefaction and liquefaction induced lateral spreading. An area needs to have fine unconsolidated sediments comprising sands, silts, and loose gravels and a water table depth that is close to the surface in order for liquefaction to occur during a sizeable earthquake. In Christchurch the prevailing reason as to why these two features are present is because of the area's past and present coastal and river location. Past coastal and river processes have laid down these susceptible sediments and the present day location of eastern Christchurch close to the coast line means that the water table is high. High water tables also occur along river edges and this is where a majority of the liquefaction induced damages have occurred.

There is consensus among the experts that sediment type, water table depth and ground shaking are the three main ingredients that enable liquefaction to occur. The 'geology/hydrogeology' theme supports the hypothesis of this research as the theme indicates that past coastal and river environments are the core reason for why the sediments and water tables that enables liquefaction to transpire are located beneath eastern Christchurch.

4.4 Liquefaction and Lateral spreading

Because one of the most predominant phenomenon of the Canterbury earthquakes sequence was large scale liquefaction and lateral spreading it was expected that these two seismic hazards would become a predominant theme in the interviews. The experts in the previous section noted that liquefaction and lateral spreading occurred around the eastern suburbs and particularly around present and past river channels. The previous sections also explained the main components that are needed for liquefaction and lateral spreading to occur, these being fine, unconsolidated sediments, high water tables and intense ground shaking.

In this section, the theme ‘liquefaction and lateral spread’ will aim to describe the process of both liquefaction and in particular liquefaction induced lateral spreading, which was the main perceived cause of damage to residential areas during the earthquakes. This theme will also cover what the previous awareness was in terms of the liquefaction and lateral spreading hazard potential in Christchurch. This is important as it appeared that these phenomena were not well understood by the people of Christchurch and it was a great shock to many to the extent at which these hazards occurred.

During an earthquake, significant damage can result from ground movement and the instability of soils affected by seismic waves (Javadi *et al.* 2006). The seismic energy required for liquefaction to occur is an earthquake creating a PGA of 0.1 *g* or greater. This equates to an earthquake of magnitude Mw 5.0 or greater (Saunders and Berryman, 2012). The “*Risk and Realities”* report (1997) indicated that the maximum magnitude of an earthquake felt in Christchurch, either from a fault rupture close to the city or farther away on the Alpine Fault, was postulated to be Mw 5.0 to 6.9, producing PGAs of 0.15 to 0.60 *g*, with a return period of 1/150 years. This meant that the occurrence of liquefaction was postulated to have a 1/150 year return period. The February 2011 earthquake was an Mw 6.3 which would normally produce PGAs of 0.15 to 0.60 *g*, as said above (Saunders and Berryman, 2012). However, this earthquake induced PGAs of 2.2 *g*, which were some of the highest recorded PGAs recorded worldwide and consequently induced more significant liquefaction than previously expected.

The occurrence of liquefaction during an earthquake results in two ground deformations known as ground settlement and lateral spreading and both can cause serious damage to manmade structures (Shamoto *et al.* 1998; Valsamis *et al.* 2010) (Figure 4.4; 4.5). Lateral spreading is the term used to refer to large horizontal ground displacements due to earthquake induced liquefaction, in the case of free ground surface inclinations including river banks (Valsamis *et al.* 2010) (Figure 4.4). Total and differential settlements, lateral movements and flooding due to liquefaction and lateral spreading are estimated to have affected 15,000 residential properties and buildings in Christchurch and in particular the suburbs east of the CBD, along the Avon River (Cubrinovski *et al.* 2011) (Figure 4.7).

"Liquefaction and lateral spreading, which is when very soft country looses strength in earthquakes and begins to move down hill, typically seen in river banks where chunks of the bank slide down and compress the river bed; old river beds and active river beds" (Professor Emeritus R.M. Kirk – 9/8/2012).

"At rivers you have the free [unsupported] surface of the banks that you can get lateral spreads going towards the rivers so that is why things were worse around the eastern suburbs and particularly by the rivers" (Dr. Marion Irwin – 30/8/2012).

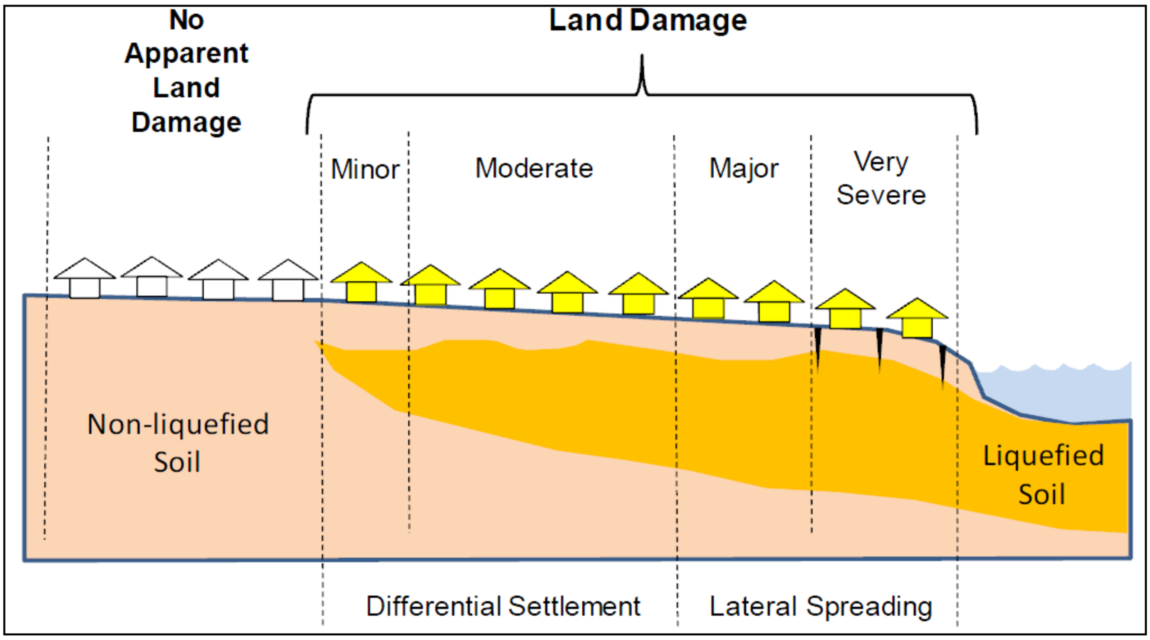


Figure 4.4: Diagram showing how liquefaction and lateral spreading causes land damage and how observed damage often correlates with distance from river banks (Source: Jacka and Murahidy, 2011:6).

Initial liquefaction occurs when the excess pore pressure approaches the confining pressure under earthquake loading where and as a result of a rapid dramatic loss of soils strength; it can initiate movement in large blocks of soil from a few centimetres to tens of metres (Prakash *et al.* 1992; Javadi *et al.* 2006). Lateral spreading occurs on gentle slopes ranging from 0.3^0 to 3^0 on loose sand with ground water levels fairly close to the surface (Javadi *et al.* 2006). The extensive cracking and subsidence that accompanies lateral spreading can cause landslides, that block transportation routes, interrupt communication lines, and damage structures built in their path (Prakash *et al.* 1992) (Figure 4.5).

"Along river banks the basic process is that if you have a high, steep bank with no cohesion the soil would just collapse under gravity because nothing is holding it together..... Spaces between the soil particles in river areas are filled with water and it is the water that carries a

lot of the above sediment load and when you start shaking the ground, you crank up the pore water pressure and that makes the water start to carry all of the load and if there is no contact between soil particles all of sudden the soil will start to flow. So it will flow down slopes and for example down stream banks" (Dr. Murray Hicks – 23/8/2012).

"Those susceptible areas can be summed up by their elevation, geology and hydrogeology and by how much the ground shakes, as some areas that could have liquefied did not because the shaking was not intense enough. It is the frequency of shaking that is more important for liquefaction to occur than the acceleration of the earthquake" (Justin Cope – 30/8/2012).

The following quotes by the experts look at the previous recognition of the seismic hazard risk in Christchurch and in particular the risk of liquefaction and lateral spreading. Overall it appears that there was previous recognition of the risk of liquefaction and recognition of where it would most likely occur if there was to be a large earthquake in the Christchurch vicinity. However it appears that this recognition was within scientific research and council realms alone and that the public awareness of liquefaction risk was lacking. It also appears that the severity to which Christchurch experienced liquefaction and lateral spreading went far beyond the expectation of the known risk.

Maps were made in the 1997 publication of *'Risk and Realities'* which showed the areas of Christchurch that could liquefy during an earthquake and these ended up being a very good indicator of where liquefaction was likely to occur (Figure 4.6). However, this map only showed zones where liquefaction could occur and what percentage of the different zones that are likely to liquefy, and did not give details as to the severity of the likely liquefaction. The quotes below highlight the expert's view on liquefaction risk in Christchurch and what they thought about the previous risk of earthquake induced liquefaction.

"Christchurch already had liquefaction maps and they were a very good predictor of liquefaction. City planners did know about liquefaction potential but did not believe that it would actually happen" (Dr. Matthew Hughes – 6/8/2012).

Figure 4.5: Photos showing the extent of lateral spreading damaging land and roads around the Avon River after the February earthquake struck (Source: Tonkin and Taylor, 2011)

"The Christchurch Lifelines group drew attention to the seismic risk in Christchurch, admittedly more to an Alpine fault rupture risk and drew strong attention to the risk of liquefaction in Christchurch. They created maps and chapters were written about liquefaction. No council in Christchurch can say that they didn't have information about seismic risk or liquefaction" (Professor Emeritus R.M. Kirk – 9/8/2012).

The above quotes recognise that there was previous awareness of liquefaction risk in Christchurch and R.M. Kirk clearly indicates that the council could not say that they were not aware of this risk. However, the following quote by council worker Graham Harrington indicates that the council did not really address the risk of liquefaction because it was not considered a major risk in Christchurch. Matthew Hughes indicated that even though the council was aware of this risk, there must have been a feeling that liquefaction would not actually happen and subsequently was not a risk that needed much consideration. This is most likely because liquefaction was a hazard that had not occurred before in Christchurch, in such severity, that would make it a priority to plan against. In other words, because the hazard had not happened in the past, it was thought to be unlikely to happen in the future. The below quote from council worker Graham Harrington re-iterates this point:

"It was known that these areas are susceptible to liquefaction and lateral spreading but it was a surprise that there was so much damage, the potential extent of the damage observed was not recognised. The idea of liquefaction was known about but not really addressed. It was not really addressed because it was beyond people's experience to deal with. Earthquakes were never a major risk in Christchurch" (Dr. Graham Harrington – 30/8/2012).

It is apparent from the literature reviewed in Chapter Two that earthquakes were in fact a major risk in Christchurch, because of the city's close proximity to active faults in the Canterbury foothills and the Alpine Fault. Graham Harrington indicates that earthquakes were not a major risk in Christchurch because the risk from a fault rupture within close proximity to the city was not recognised. This is because, as discussed in Chapter Two, the risk of a fault rupture close to the city is unknown, because the existence of past active faults is hidden by deep alluvial gravels. An earthquake either from afar or nearby, in reality, is a major risk in Christchurch, consequently so is liquefaction and it appears now that city planners had ignored the indicators of this risk either intentionally or un-intentionally.

The following quotes by Shamus Wallace and Justin Cope re-iterates Matthew Hughes' point that until a hazard actually occurs people are less likely to recognise and take action to minimise the risk. The quote below highlights that homes in Christchurch were built to a standard that would survive a sizeable earthquake and that the risk of an earthquake in Christchurch was at a level that was acceptable to build and buy homes in Christchurch. This quotes also highlights that the Christchurch public were relatively oblivious to the real risk posed to them by earthquake induced liquefaction, even though earthquake risk was highlighted within public preparedness strategies, liquefaction appears to have not been.

"There was an awareness of risk in building plans but the expectation of a 1 in 2000 year earthquake event meant that the risk was at an acceptable level to build and buy houses in these areas. However many people were not aware of the risk at all as it was not published because of the low risk of earthquakes in Christchurch. The hazards were recognised and

published, the information was there, but the public awareness perhaps was not well understood. It's not until the hazard has occurred that people recognise and take on board the hazard" (Shamus Wallace – Engineering Geologist, Team Leader in Assessments and Investigations of Land Damage at Tonkin and Taylor – 27/8/12).

"It is a shame that this entire earthquake research is being done now and not previously which would have been more proactive, but that is the way things go. I have learnt that you can expect things to happen and you can expect the worst but the scale of this disaster, how many people were affected, the area that was affected , you knew there were susceptible areas but the scale went beyond the expectation of the worst case scenario" (Justin Cope – 30/8/2012).

The above quote by Justin Cope indicates that even though areas of Christchurch that are susceptible to liquefaction were recognised, the extent to which damage occurred in these areas went beyond expectations. The *Risk and Realities* maps from 1997 and the map from Elder *et al.* (1991) did indicate zones of potential liquefaction (Figure 4.6) but they did not indicate the severity of liquefaction (low/moderate/severe). They noted what could happen to lifelines when liquefaction occurred but did not identify the extent of this damage. Much of the liquefaction that was recorded during the September 2010 and February 2011 earthquakes occurred in areas predicted by Elder *et al*. (1991).

However, the areas northwest of the CBD experienced significant liquefaction during the February 2011 earthquake (Figure 4.7) that Elder *et al* did not predict to be significantly susceptible to liquefaction. Widespread liquefaction in eastern Christchurch during the September 2010 earthquake is consistent with the prediction that "20 to 30%" of this area "could liquefy" in the *Risk and Realities* 1997 map. However, the February 2011 earthquake, again, appears to have caused more liquefaction than predicted in the CBD and areas northwest of the CBD (Figure 4.7). This could be why the experts note that the effects of liquefaction were beyond the expected scale and extent of predicted liquefaction, they meant the spatial scale and extent was exceeded, if only by a little, but that the damage liquefaction and lateral spreading caused significantly exceeded expectations.

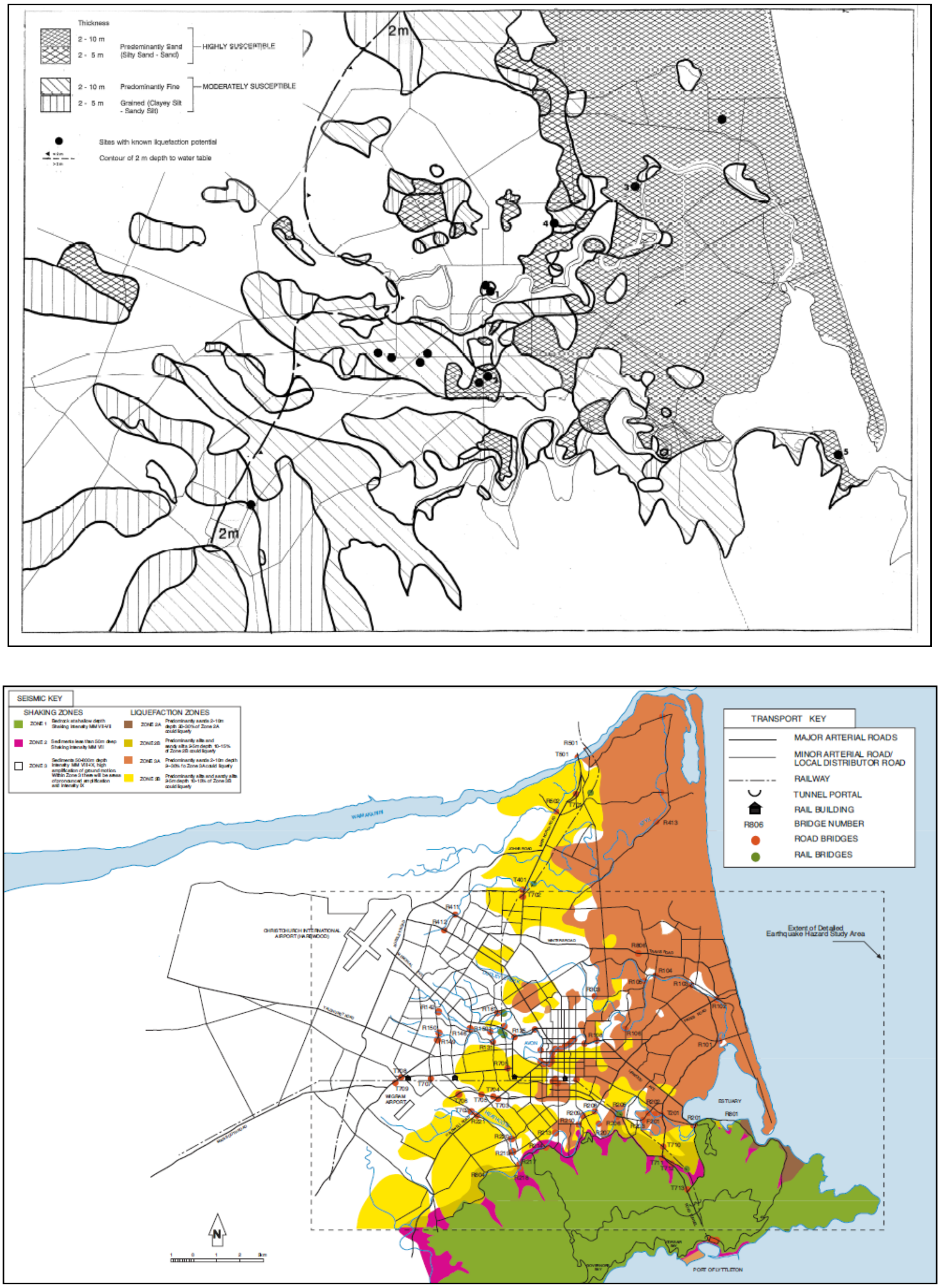


Figure 4.6: Top figure shows liquefaction susceptibility for Christchurch (Source; Elder et al. 1991). Bottom map from: Risk and Realities 1997, shows zones of soil types within Christchurch that could liquefy in an earthquake.

This section has summarised the process that caused sediments in eastern Christchurch to liquefy during the Canterbury earthquakes. This section also described the processes of liquefaction that caused the phenomena of lateral spreading and land settlement which are ground deformation features that caused a majority of the damage seen in the residential areas of Christchurch. The previous awareness of liquefaction potential was also addressed in this section. The experts agreed that there was a major risk to Christchurch from an earthquake as a result from a fault ruptures on either the Alpine Fault, in the Canterbury foothills or on an unknown fault close to the city, all three of which, would induce significant ground shaking over the city. Because New Zealand sits on the Pacific Ring of Fire, earthquakes are a major risk to the entire country and strict building codes are in place because of this risk.

There was consensus among the experts that there was previous recognition and understanding about the potential for liquefaction in eastern Christchurch. However, this risk appears to have been overlooked or not considered proactively, because it was a hazard that had not occurred previously in Christchurch, as Matthew Hughes said, "[the council] *did not believe that it would actually happen"* and Shamus Wallace quotes "*it's not until the hazard has occurred that people recognise and take on board the hazard".* The experts agreed that even though there was recognition, it was not advertised enough so that the people in Christchurch understood the risk, even though the risk should have been a part of their LIM. The issue with relying on LIMs to relay hazard risk information is that only the property owner obtains the LIM not renters that reside within the property and even then only 10 to 20% of people purchasing properties actually request a LIM, usually due to the expense (Harker, 2011). The experts also agreed that the severity to which liquefaction and lateral spreading occurred in Christchurch was unprecedented and the amount of damage it caused went beyond previous reckoning.

The 'liquefaction and lateral spreading theme' contributes to the hypothesis of this study. The reason for why liquefaction and lateral spreading occurs is imbedded within past and present coastal and river processes. The theme adds depth of understanding of the main drivers of damage observed in Christchurch and confirms that a majority of damage due to liquefaction and lateral spreading was in the eastern suburbs and predominantly around rivers and estuarine environments. This section also addresses how previous understanding of hazard potential can play a significant role in reducing a city's vulnerability. A city's vulnerability to hazards such as earthquake induced liquefaction can be significantly reduced with an increase in knowledge about hazard potential coupled with greater awareness and understanding of the risk by both the public and governing bodies, not just experts.

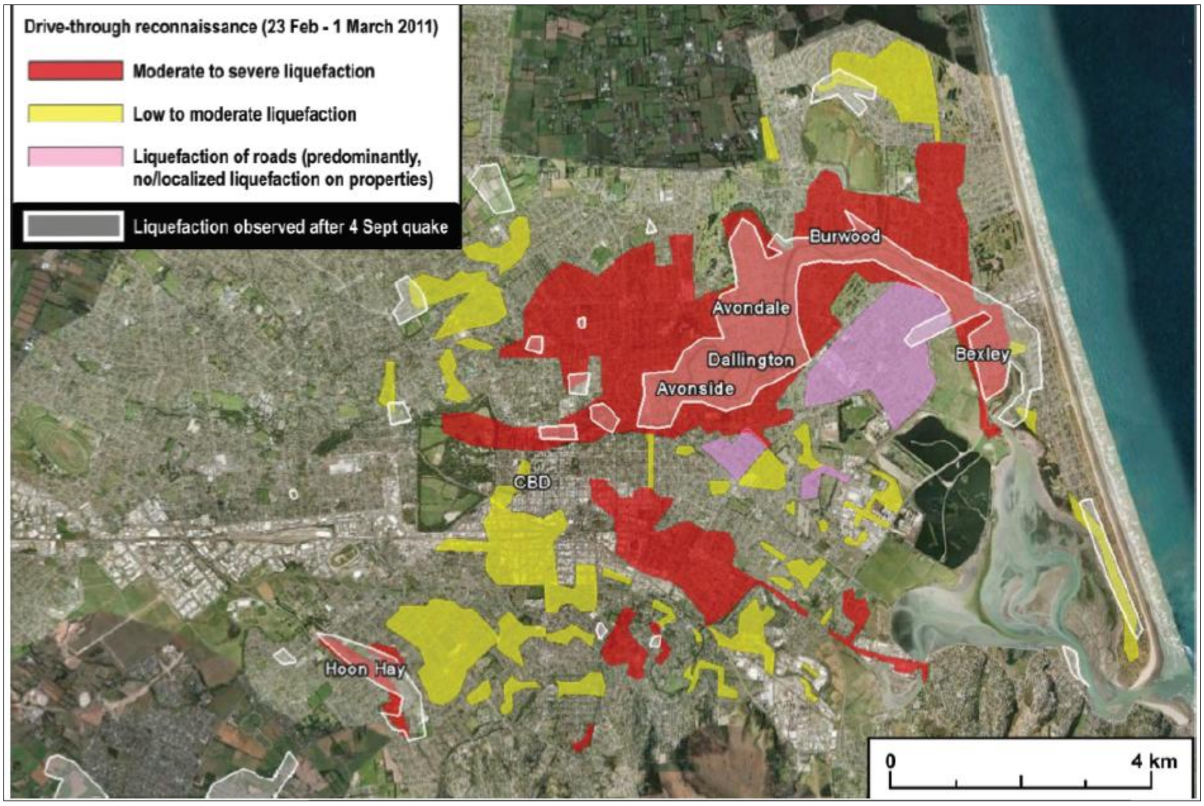


Figure 4.7: Areas of observed liquefaction in Christchurch due to the 22 February M w 6.2 earthquake (coloured areas) and the Mw 7.1 Darfield main shock (white contours) (Source: Cubrinovski & Taylor, 2011).

4.5 Land Elevation Changes

The Canterbury earthquake sequence has caused significant changes to the elevation of the land throughout the wider Christchurch region. The experts noted numerous times that changes to the land has occurred due to land settlement and uplift particularly around coastal areas, rivers and the Avon Heathcote Estuary. As such, ‘land changes’ became a prominent theme within the interview responses. This theme aims to identify areas that have undergone the most significant elevation changes, why these changes occurred and lead into what the implications are as a result of these different elevation levels.

The February 2011 Christchurch earthquake fault ruptured towards the eastern fringes of the Darfield aftershock zone and only 6 km south east of the CBD. It occurred on a previously unmapped northeast-southwest striking fault that did not rupture the ground surface (Kaiser *et al.* 2012). A main point of interest for the Christchurch recovery is the amount of uplift and subsidence caused by the earthquake. The large scale tilting of the Christchurch region was a result of what is now known as the Port Hills fault rupture (Figure 4.8). Research models following the earthquake showed subsidence in the suburbs north and northwest of the estuary by up to 10-15 cm (Figure 4.9) these numbers are correct to within about ± 25%. Additional subsidence and land settlement was a result of ground failures such as widespread liquefaction and associated lateral spreading (Kaiser *et al.* 2012). In some areas, settlements of over 1 m was measured, which is a significant drop in ground elevation given the low lying nature of Christchurch, even prior to the Darfield earthquake (Cubrinovski *et al.* 2011). The following two quotes from the expert raise awareness to the large scale tilting of the Christchurch area:

"The area [southern Christchurch] has been raised by half a meter and changed the relationship with sea level and wave action by half a meter in one direction. Most of the urban frontage of the city, two thirds, has dropped half a meter which has its circumstances physically changed in that direction" (Professor Emeritus R.M. Kirk – 9/8/2012).

"There has been large scale tilting of the ground as well as local buckling. The tilting seemed to be focussed from the Port Hills trace fault." (Dr. Murray Hicks – 23/8/2012).

The following quotes highlight the changes that occurred along the Pegasus Bay coastline and the lower Avon River as well as highlighting potential changes to coastal processes.

"The mouth of the Waimakariri at Brooklands the areas has sunk by half a meter. Lots of coastal land around the lower Avon has sunk by more than 2 m in some places and Bexley has gone down by 1.3 m. The estuary in the southern end has gone up and the northern end has gone down" (Professor Emeritus R.M. Kirk – 9/8/2012).

"Transport of sediment along the coast may have changed due to changes in the coastline" (Dr. Marion Irwin – 30/8/2012).

The large scale tilting of the Christchurch region has implications for the coastline of Pegasus Bay. The northern part of Pegasus Bay, around the Waimakariri River Mouth has subsided while the southern part of Pegasus Bay, near the southern end of the Avon Heathcote Estuary has uplifted. This has many implications for current coastal processes including the sediment budget of the Bay which may lead to either erosion or accretion of the shoreline. Importantly, these changes have not been researched yet, so knowing which way the sediment budget may change is still uncertain. These effects to the coast line and to rivers again underpin the concept of vulnerability in coastal and river areas. The large scale and localised subsidence and uplift of coastlines and rivers have significant implications for current river and coastal hazards. These hazards will be clarified and discussed further in the next section.

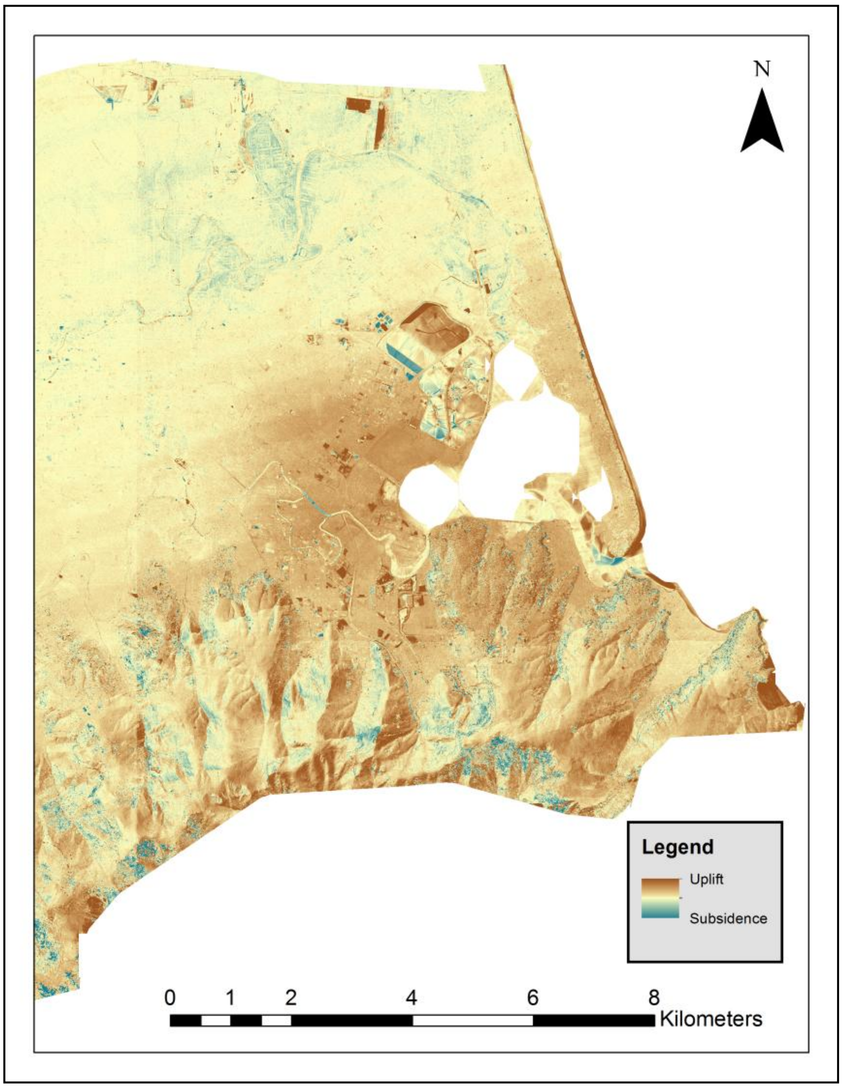


Figure 4.8: Map of the wider Christchurch area showing areas of uplift in red and subsidence in blue, as a result of the February earthquake, February 2011.

4.5.1 Impacts on the Avon Heathcote Estuary

A prominent sub theme within the 'land changes' theme was identified as the 'Avon Heathcote Estuary' theme. Significant land changes occurred throughout Christchurch but particularly large scale changes occurred on the surface floor of the Avon Heathcote Estuary. This theme is important to identify as the changes within the estuary have greater implications for the long term stability of the sediment budget of wider Pegasus Bay. There is also significant implication for flooding along the fringes of the estuary in areas of land subsidence especially during storms. This section will focus on the changes that have occurred to the level of the estuary floor and will focus on the implications that these changes have on the sediment budget of the estuary and the surrounding beaches of Pegasus Bay. The implications of these land changes in the estuary that are associated with other coastal hazards will also be discussed in a later section.

A report by NIWA showed that the northern part of the estuary, where the Avon River discharges, has subsided by 0.2-0.5 m while the southern end, which includes the estuary mouth and the Heathcote River has uplifted by 0.3-0.5 m. (Measures *et al.* 2011). The average elevation change over the estuary (relative to mean sea level) was a rise of approximately 0.14 m. This would mean that there has been a reduction in the mean prism volume of around 1 million m^3 which is roughly 14%. The overall tilting of the estuary floor means that the extent of inundation within the estuary with each tide has also changed (Figure 4.9). The largest change in inundation area occurs at mid-tide such that, overall the area exposed at this level has increased by 18%. In particular the area in the south west of the estuary was once inundated at mid-tide and is now dry (Measures *et al.* 2011). The resulting changes in estuary hydrodynamics will affect the distribution of chemical and biotic features. This is due to the changes in habitat, which result from being either more inundated or exposed on each tide, however it has been established that biotic distributions will eventually adjust to the new inundation regime (Zeldis *et al.* 2011).

"Looking at the estuary, the southern end has uplifted by half to one metre in places which is a lot in terms of the amount of water that enters the estuary. Tidal intrusion is higher up the Avon River due to general subsidence in the northern end. The whole estuary floor has tilted: more of the southern end is now exposed and northern end is now more inundated. There are obvious effects of inundation including a big puddle up in the north end and bar and sediment banks are now more exposed in the southern end" (Dr. Murray Hicks – 23/8/2012).

"We have lost 14% of the volume of the estuary's tidal volume, lost 2 million cubic meters of water. The estuary breathes by taking on water on each tide. The size of the entrance to the estuary changes with changes made to the estuary volume. So because the estuary volume has changed the entrance is likely to change which will causes changes to the Spit, Sumner and red cliffs. The Sumner Bar has a volume that is also related to the estuary volume, and

the bar is now too big relative to the tidal volume, so does that mean the bar will shrink? Which means half a million yards of sediment will be released? Where will it go?" (Professor Emeritus R.M. Kirk – 9/8/2012).

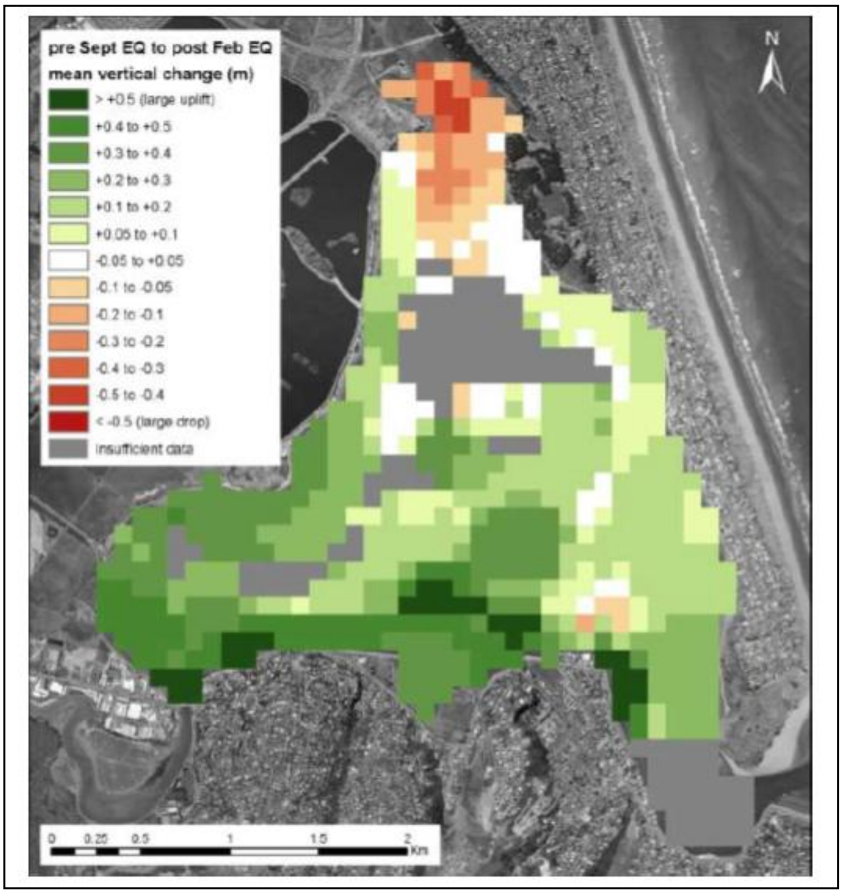


Figure 4.9: Map showing vertical changes to the estuary floor elevation from September 2010 earthquake to post February 2011 earthquake (Sources: Measures et al. 2011: 14)

In consequence to the northern edge of the estuary subsiding, the likelihood of flooding along the shore, during extreme high tides and during storms is likely to increase. In addition there will likely be erosion of the salt marsh and reed banks due to deeper water and consequent increased wave energy and swifter tidal currents. In the south of the estuary where more of the floor is exposed it is predicted that wave energy will decrease because wave energy is less with shallower depths and shortened inundation at high tide. This will influence substrate stability and habitat and less wave energy may result in a muddier substrate (Measures *et al.* 2011). A reduction in the tidal prism of the estuary could mean that the inlet near Shag rock may narrow and the volume of material stored in the tidal deltas to reduce as a result. Hicks and Hume (1996) found that the tidal inlet cross-section area and volume of sand on the tidal deltas relates linearly to the tidal prism volume (Figure 4.10), thus a 14% reduction in the Avon Heathcote Estuary inlet area may be expected.

Using the empirical relation of Hicks and Hume (1996), a 14% reduction in tidal prism should reduce the ebb delta volume by about 18%. This reduction in volume would release surplus sand which would nourish the adjacent beaches (Measures *et al.* 2011). However, it is uncertain that this will be the case. Other experts have voiced opinions that there could be changes within the estuary tidal prism itself that would enable the tidal prism to increase again through erosion processes and reach an equilibrium state again with the inlet and tidal deltas.

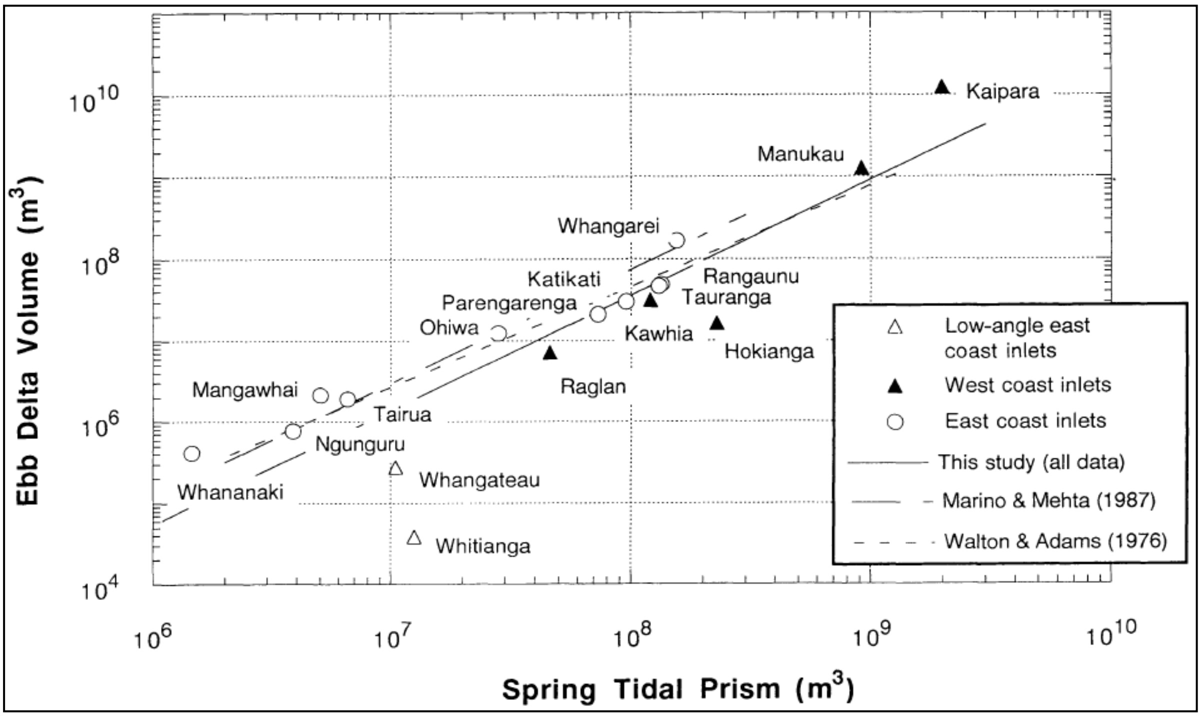


Figure 4.10: Relationship between ebb tidal delta sand volume and tidal prism for New Zealand estuaries. Figure shows that the larger the tidal prism the larger the volume of sand is on the deltas (Source: Hicks and Hume, 1996:59).

This could be reached by the estuary eroding and increasing the tidal prism to its original state, or it could be a combination of estuary and inlet/delta responses that could occur simultaneously in order to reach equilibrium. Further studies are needed in order to recognise what direction of change will take place within this dynamic environment and monitoring of these responses will be an important aspect of the Christchurch recovery process. These studies need to include continual updates on the elevation of the estuary floor, hydrodynamic models that indicate changes in circulation and hydraulic behaviour and morphological models that indicate sediment redistribution.

The following quotes reiterate the processes that occur within the Avon Heathcote Estuary given the changes in the tidal prism post the earthquakes.

"The inlet at shag rock and various sand deposits, tidal deltas, scale with the size of the estuary, and because the estuary size has decreased it could mean that the inlet may narrow or tidal deltas to get smaller. This means that the sediment that formed the inlet and deltas has to go somewhere else and the reality is that they are equilibrium deposits so sand comes on them and get pushed in and out of the inlet and exchange within the inlet and the flood deltas and the adjacent beaches. The likely response would be that the sand stored at those deltas would then be available to the adjacent beaches which are positive effects" (Dr Murray Hicks – 23/8/2012).

The above quote by Murray Hicks makes the same assumption as the previous quote by R.M. Kirk that changes within the dynamics of the Avon Heathcote Estuary will occur following the earthquake sequence. The changes to get the equilibrium back are evident but the direction of change is not evident. Meaning that whether or not it will be the estuary's tidal deltas and inlets that will change size to get back to equilibrium with the tidal prism or the tidal prism that will change size to get back to equilibrium with the inlet and deltas is uncertain.

"Changes in the tidal prism in the estuary have implications for surrounding beaches in terms of more sediment available from the erodible deltas. More sediment is helpful or not depending on the management perspective, sometimes there is a battle with too much sediment from a planting of vegetation point of view. From a coastal hazard perspective an excess amount of sediment is a good thing" (Justin Cope – 30/8/2012).

The above quote indicates that if the tidal deltas become smaller, as a result of adjusting to the reduced size of the tidal prism, there would be a release of sediment to Pegasus Bay. This excess sediment, as indicated by Justin Cope, Murray Hicks and R.M. Kirk would then be available to the surrounding beaches. As indicated in the above quote, this excess sediment is a good thing from a coastal hazard perspective, as excess sediment in beach sediment budgets means the beach is less susceptible to erosion.

As well as changes to the estuary's topography as a result of the earthquakes the Avon Heathcote Estuary also experience significant liquefaction. The proportion of the estuary bed covered by liquefaction was substantial, around 20 to 40% (Figure 4.11). There was a large density of liquefaction mounds covering the eastury ranging from 500 to 3500 mounds per hectare, over the entire estuary the average mound surface area varied from 1 to 5 m^2 (Measures *et al.* 2011). One issue concerned with liquefaction inside the estuary is that the process exhumed sediments potentially contaminated heavy metals, organic matter or nutrients, which had been buried beneath the estuary bed. The release of these sediments has the potential to affect the water quality of the estuary and subsequently affect the biota that resides there (Zeldis *et al.* 2011). Subsequent monitoring of the estuary's habitats and biota are ongoing.

Figure 4.11: Photos of the liquefaction mounds that covered the Avon Heathcote Estuary (Source: Red Zone Tours, 2012)

This section has highlighted that the earthquake events have significantly altered the elevation of the Avon Heathcote Estuary, which has implications for both the morphodynamics and the hydrodynamics of the estuary. The Avon Heathcote Estuary is influenced by both river and coastal processes and has proven to be susceptible to effects brought about by the earthquakes. This environment has been effected to the extent that the present biological habitats within the estuary have been altered as well as the chemical makeup of the substrate and water column. This change in hydrodynamics potentially has implications for the sediment supply within the estuary and the surrounding coastline of Pegasus Bay. The potential for the coastline to either lose sediment or increase sediment as a result of changes caused by the earthquakes, significantly contributes to the vulnerability of coastal environments.

4.5.2 Effects on Coastal and River Hazards

The above section has highlighted that the earthquake events have had an influence on the land elevation of the Christchurch region and in particular the Avon Heathcote Estuary, the Lower Avon and northern Pegasus Bay. This change in elevation has implications for current coastal and river hazards that exist within the Christchurch region. Sonia Giovinazzi noted that *"there is awareness that other hazards have been influenced"* and it would seem necessary to assess these hazards as part of the rebuild process. Dr Justin Cope noted that *"the earthquake events haven't created new hazards but have exacerbated existing ones"* and the extent to which these hazards have been exacerbated is a main topic of this section. This section's theme is "natural hazards" and it will aim to discuss the main hazards that were discussed during the interviews. The three main hazards that were discussed by the experts were flooding, tsunami and sea level rise. The following subsections will focus on each of these hazards individually.

4.5.3 Flooding

Flooding is the most common natural hazard to affect Canterbury with vast areas of the region vulnerable to a degree of flooding risk. The three main types of flooding that affect Canterbury are river flooding, coastal overtopping and local runoff flooding (Environment Canterbury, 2012).When the February earthquake struck the slip in the fault caused the Christchurch region to subside in the northern suburbs and uplift in the southern suburbs, as evident in figure 4.8. This subsidence in the north is heightened in places where lateral spreading and liquefaction has caused further settlement of the land (Kaiser *et al.* 2012). Because there has been significant subsidence of large parts of the city, there is increased risk of flooding from both extreme high tides at the river mouths and river flooding caused by extreme rainfall events. These areas, now prone to a higher risk of flooding, mostly, coincide with residential red zones, which take the risk to people and property in these areas, out of the equation (Cubrinovski *et al.* 2011). The additional subsidence has also caused the exacerbation of existing flooding problems in the low lying suburbs north and northwest of the estuary that have not be red zoned (Kaiser *et al.* 2012). The following quotes by Dr

Graham Harrington and Professor R.M. Kirk explain how subsidence caused by the earthquakes has exacerbated flooding risk in Christchurch:

"Coastal areas have been affected to the point that they suffered land settlement so are now subject to increased tidal flooding. Land settlement in coastal areas has implications for long term coastal erosion and aggradation and other changes. The fact that you don't have the outfall level that you used to have, the sea is now relatively higher, so land does not drain as well as it did before. Water cannot drain as well off the land because of changes to the ground level. This has implications for flooding" (Dr. Graham Harrington – 30/8/2012).

"The estuary in the southern end has gone up and the northern end has gone down which causes flooding in the lower Avon. The highest water levels in the estuary are caused by storm surge, low pressure systems and the amount of water running off from the city due to the same storm system. Because the estuary is raised up by half a meter in the southern end and has a big pond at the northern end this has a huge implication during storms" (Professor Emeritus R.M. Kirk – 9/8/2012).

The above quotes have indicated that land settlement and the tilting of the estuary and the Pegasus Bay coastline have implications for coastal flooding. The northern part of the estuary, where the Avon River discharges has subsided by 0.2 to 0.5 meters which leads to flooding along the shore line with extreme high tides and exacerbates erosion of the banks (Measures *et al.* 2011). Many low lying parts of coastal Canterbury are prone to coastal (sea water) inundation which can endanger stock and cause long term damage to farm land. Coastal inundation occurs when a combination of high tides, low pressure systems, on shore (easterly) winds and heavy swells drive the sea up and over beach crests. In northern Canterbury *"the mouth of the Waimakariri at Brooklands...has sunk by half a metre" (Dr (Professor Emeritus R.M. Kirk – 9/8/2012).* and this means it would need less of these combined factors to be able to overtop the beaches.

The following two quotes by Dr Shamus Wallace and Dr Murray Hicks highlight the issue of river flooding within Christchurch post the earthquakes.

"Land forms have changed, which influences flooding risk in areas of flat terrain..... The influence of storms and rain has caused more surface flooding in areas around rivers and flat land. This was observed in a recent high rainfall event in Canterbury." (Shamus Wallace 27/8/2012).

"Assessments were undertaken to look for blockages and any other damage that has occurred to the rivers and stop banks. In the lower Avon in particular, there are stop banks for protection against tidal flooding. These stop banks were damaged during the earthquake and because a lot of homes are located close to the river they were also affected by lateral spreading, slumping and the ground levels lowering. So if the stop banks were not fixed quickly, then those homes would have been impacted by tidal flooding." (Dr. Graham Harrington – 30/8/2012).

Emergency stop banks were initially constructed due to the expected spring tides in April 2011. 11 km of stop banks were built over four days along the Avon River. "*Extra gravel had to be poured along the river edges to help stop flooding in the lower Avon" (Professor Emeritus R.M. Kirk – 9/8/2012).*, these were built up to 1.8 m above mean sea level. Lateral spreading cracks were filled prior to construction of the stop banks and the stop banks themselves were made of silty gravel which was readily available and reasonably impermeable (Cubrinovski *et al.* 2011). The construction of the stop banks around Bexley Wetland meant that the area, that was once above the high tide water mark are now below the crest of the stop banks, once again showing how much the land has subsided in this area and the consequences of this in terms of coastal hazards (Figure 4.12). Fortunately, these stop banks performed well and prevented coastal flooding during the spring tides following the February event. Subsequent to the construction of the first emergency stop banks a total of 17 km of stop banks was created from the mouth of the Avon River up to the suburbs of Avonside. Flood levels along the Avon River are approximately 3 m above mean sea level which meant that the stop banks had crests rising 1.4 m above the current ground level in some places (Figure 4.12).

The over arching 'coastal hazards' theme examines how the earthquake events have exacerbated pre-existing hazards, the earthquake events have not just created new problems but have highlighted old ones. Flooding in estuarine and river mouth areas and along low lying river areas is an existing hazard in Christchurch. The earthquake events have not created a new flooding hazard as Christchurch was vulnerable to flooding before the earthquake sequence began. Flooding in Christchurch occurs because of the low lying nature of the area and historically the region's rivers cause flooding events on a regular basis due to high rainfall events. However, the earthquakes have exacerbated flooding hazards due to further lowering of the land that was already at risk of flooding events. A question that could be raised is whether or not the flooding hazard prior to the earthquakes was at an acceptable level and what can be done now to enhance the city's resilience to flooding hazards in both coastal and river areas.

The below quote by Dr Murray Hicks highlights the problem faced by both coastal and river environments in terms of flooding hazards and notes that there is work that is being done to try and understand these changes and how they affect coastal and river vulnerability.

"As a consequence of the earthquakes and changes in the level of the land and deformation of banks has caused the flooding hazard to change both in the coast and rivers....there is however, a lot of work going on to understand the implications of these changes to flooding hazards in Christchurch and how that effects the vulnerability of certain areas" (Dr. Murray Hicks – 23/8/2012).

Figure 4.12: Photos showing the emergency stop banks that were created around Bexley Wetland (left) and along the Avon River (right). Photos show the higher water level compared to that of the land.

4.5.4 Tsunami

For the Canterbury coastline between the Waitaki River Mouth and the Hurunui coast the biggest tsunami threat is a distant source tsunami generated off the coast of South America and potentially Central America. Tsunami waves travel very quickly across the ocean and Canterbury has a 12-15 hour travel time of a tsunami generated from South/Central America (Gillibrand *et al.* 2011). The particular problem associated with tsunami hazards in Christchurch is to do with the changes in the elevation of the lower Avon River and the Avon Heathcote Estuary. Because the lower Avon River and the northern part of the estuary is now at a lower elevation, the impacts of a tsunami in this area are likely to be greater.

"After the quake because of subsidence and lower ground the tsunami modelling had to re run to see if the inundation level of a tsunami had changed and there is more inundation in some places. There is more inundation along the red zone and around Brighton and more in the Northern Waimakariri area" (Dr. Marion Irwin – 30/8/2012).

The tsunami modelling report provided by Environment Canterbury in 2011 predicted maximum wave heights in Pegasus Bay from a distant source tsunami to be 2-2.5 m (Gillibrand *et al.* 2011) and these modelled wave heights are likely to be different now given these changes in elevation. Environment Canterbury is currently re-assessing potential flooding in Christchurch from a worst case scenario distant tsunami given the changes to ground level in these areas after the 2010 and 2011 earthquakes. These changes are likely to change coastal evacuation zones for distant source tsunamis in these areas (Environment Canterbury, 2012). Although the return period for a worst case scenario tsunami is relatively low (~2000 year return period) the effects of such an event is a significant hazard and should be considered in the rebuild plans of the city especially in terms of rebuilding in areas of low elevation and close to the coastline.

4.5.5 Sea Level Rise

Due to anthropogenic global climate change, average global sea-levels are rising. The warming of the Earth's temperature causes ocean thermal expansion and melting of ice from glaciers and polar ice sheets (Pethic, 2001; Cronin, 2012; Woodroffe and Murray-Wallace, 2012; Gehrels and Woodworth, 2013). Global sea levels rose 10 to 25 cm over the last century and are expected to rise by about another 0.5 m by 2100 (Gornitz, 1991; Warrick *et al.* 1996). Recent measurements show that actual sea level rise is occurring faster than predicted (Cronin, 2012) and mitigation measures would slow, but not stop, the expected rise, even given the stabilisation of greenhouse forcing in the next few decades (Nicholls and Mimura, 1998). Subsequently adaptation to sea level rise will be essential during this next century for people who live in coastal communities (Woodroffe and Murray-Wallace, 2012). Anticipated coastal impacts include: inundation and displacement of wetlands and lowlands, coastal erosion, increased coastal storm flooding, salinisation and associated impacts on coastal cities, infrastructure lifelines, and communities (Barth and Titus, 1984; Pethic, 2001).

In New Zealand, records are kept in three places, Auckland, Wellington and Christchurch. These record gauges have shown an average rise in relative mean sea level of 1.6 mm per year over the 20th century, around 0.16 m per century (Hannah, 2004). The Ministry for the Environment models indicate that a New Zealand sea level are predicted to rise by 0.5 m by 2090 and advises that planning assessments should consider the consequences of a rise of 0.8 m by 2090 (Figure 4.13).

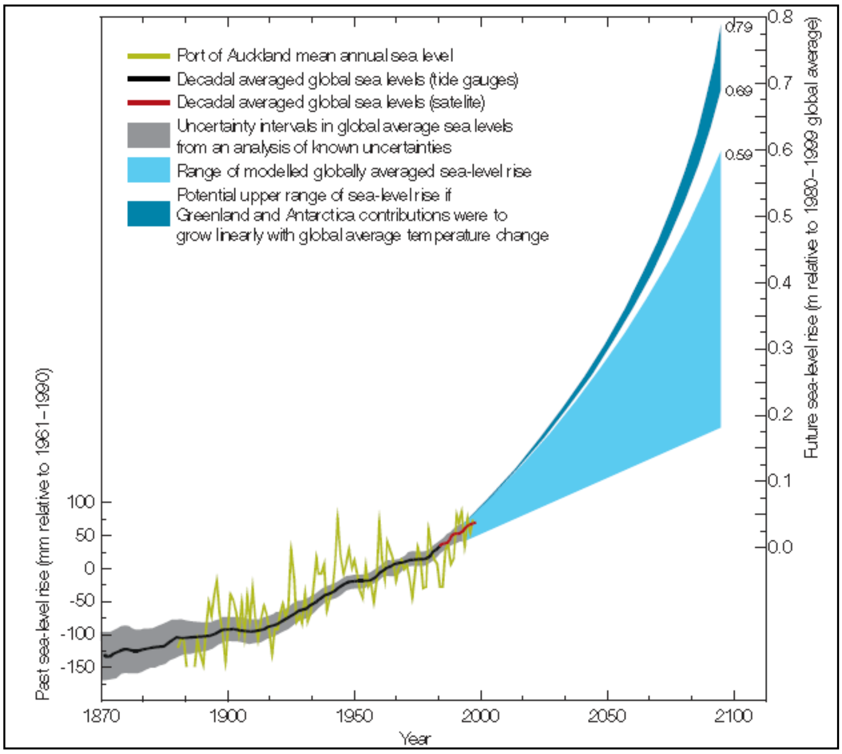


Figure 4.13: Graph showing observations of past sea level rise and projections of future global mean sea level rise to the mid 1990s (Source: Ministry for the Environment, 2013)

"Sea level rise issues within the lower reaches of the rivers that have sunk. A city council map has been created showing the effects of sea level rise on Christchurch based on the MFE guideline (+.5 m in 50 years/ +.8 m over 100 years). If you look at the inundation sites from that map they match up with areas that have been red zoned" (Justin Cope – 30/8/2012).

In the event of an earthquake, the land may subside and then sea levels around this land become higher than it was before, this is a rise in sea level over a matter of seconds rather than decades. With the occurrence of the Canterbury earthquakes, in areas where there has been tectonic and liquefaction subsidence, including the northern end of the Avon/Heathcote Estuary and northern Christchurch coastline, relative sea-level rise occurred over a matter of seconds. This subsidence now has implications for the long term planning of the Canterbury coastline with regard to further long term sea level rise. The below quote from Professor

R.M. Kirk illustrates the significance of this subsidence in association with long term sea level rise issues:

"Ministry for the environment documents on sea level change, says to allow for 1 m sea level rise over the next century, but the earthquakes have caused the northern coast line of Pegasus Bay to go down half a meter which has added 200 years of sea level rise to the already known 22 cm rise that has already occurred over a matter of seconds. So how can there be a policy that says you should prepare for 1 m of sea level rise when these changes have occurred. If you're going to plan for sea level rise in Christchurch you now need three different numbers to plan for not one. You need one for where coastline has not changed, one for where the coast has uplifted and one for where the coast has subsided post the earthquakes" (Professor Emeritus R.M. Kirk – 9/8/2012).

The above quote by R.M. Kirk indicates that the subsidence and uplift caused by the earthquakes now means that different numbers are now needed for planning future sea level rise. This is because parts of Christchurch are now either lower or higher than they were before the earthquakes, resulting in the need for updated number on the projections set down by the IPPC and Ministry for the Environment.

Although the precise magnitude of future relative sea-level rise in Christchurch is unknown, rising sea levels will also lead to rising groundwater tables, which have implications for future liquefaction and flooding hazards. The land zoning issues being confronted in the wake of the Canterbury earthquakes may need to be revisited again and consider the hazards posed by rising sea levels including coastal inundation and shoreline retreat. However, the below quote from Dr Murray Hicks has a positive view about long term sea level rise with regards to the post earthquake changes:

"Due to reduction in the tidal prism there will be an offset in long term effects of sea level rise which will be good for the open coast as there is more sediment available on the beaches of Sumner and on the south end of Brighton Spit. Not sure of what the effect will be on the open coast of northern Pegasus Bay but because it has to deal with a lot of energy from storm waves any way and has a lot of sediment available anyway it can probably cope with the earthquake effects" (Dr. Murray Hicks – 23/8/2012).

The above quote makes an assumption about what might happen to the tidal prism and estuary inlet relationship, as addressed in the previous section, there a multiple options for the estuary's future adjustments.

Knowing what exactly the long term effects of sea level rise on Christchurch city will be, can only be done by continued monitoring and updating of models, as technology advances and information becomes increasingly available. Furthermore, with advancements in information, there needs to be actions taken to protect communities against rising sea levels. Unfortunately one action that could have been taken in the recovery stages following the earthquake would have been enabling the retreat of suburbs from coastal areas that are at a high risk of coastal hazards and imminent sea level rise.

The above three sections have highlighted the main hazards that have potentially been exacerbated due to the earthquakes of 2010 and 2011. These hazards are typically coastal and river hazards and include flooding (coastal and river), erosion (coastal and river), tsunami and sea level rise. As such, the 'hazards' theme supports the hypothesis that coastal and river environments are vulnerable to earthquake hazards as they are environments that are easily altered because of their dynamic nature and susceptibility to multiple hazards. These hazards are important with regard to the land zoning and rebuilding of Christchurch as they pose a risk to the long term sustainability of the city, particularly around areas close to the coast. These hazards need to be assessed and monitored in order to provide the public of Christchurch with the information they need to decide whether residing in areas, which are vulnerable to these hazards, is appropriate.

4.6 Summary

The Canterbury earthquakes have had a particularly profound effect on coastal and riverside suburbs in Christchurch and wider Canterbury. This highlights the reality that coastal and river environments may be more vulnerable to the hazards associated with seismic events including liquefaction, lateral spreading, rock falls and land settlement. This point will be important for the re-development and management of these areas in the future, for not only Christchurch but other New Zealand cities.

Field work for this section included interviews with experts from companies that have been involved with the assessing earthquake effects and involved with the rebuild of Christchurch. The first question discussed in this study is what physical features of coastal and river environments make them more vulnerable to earthquake induced hazards. These interviews revealed that the past and present coastal and river environments of Christchurch are the primary reason for why the damage in eastern Christchurch was as significant as it was. Past coastal environments laid down fine sand silts over eastern Christchurch during the last glacial post glacial rise in sea level around 7000 years ago, where the entirety of eastern Christchurch was a marine/coastal environment. Past and present river channels incise the area of Christchurch. The Waimakariri River is responsible for laying down fine gravels in the past while the smaller spring fed rivers and responsible for laying down further fine sand and silts over Christchurch in the past and the present.

The second question discussed in this section was how have coasts and rivers in Christchurch been impacted by the earthquakes. The observed damage in the CBD and residential areas around the coastline and rivers was caused by widespread liquefaction, lateral spreading, rock falls, and flooding and land settlement. These hazards were fuelled by three important factors 1) sediments, fine sand and silts 2) high water tables, 1-0 m below the surface and 3) severe ground shaking. Liquefaction caused sediment and water to be ejected to the surface which damaged homes through creating cracks in the ground and causing homes to settle and flood. Lateral spreading induced significant damage by causing large scale ground failures around rivers, where the ground moves by not only centimetres but by metres.

The fault rupture of the February event caused large scale tilting of the Christchurch coastline, resulting in subsidence in the north-eastern suburbs. This subsidence was exacerbated again in places where liquefaction induced land settlement had also occurred. This tilting also caused the northern part of the Avon-Heathcote estuary to subside and the southern part to uplift, which changed the amount of water that enters the estuary on each tide and. The subsidence of the northern part of the estuary has implication for flooding in those suburbs north of the estuary. The change to the estuary's tidal prism has implication for the inlet of the estuary, as the size of the estuary inlet has a linear correlation to the estuary volume. Since the volume of the estuary has decreased the inlet is likely to narrow and this subsequently causes the tidal deltas which stores sediment to decrease which would then provide excess sediment to the surrounding beaches of Pegasus Bay. However, it is uncertain if these predicted changes to the inlet will take place or whether the estuary dynamics will change in another way to bring the estuary and the inlet back to its original linear correlation.

The third question discussed in this section was whether the earthquakes have influenced future coastal and river hazards. The elevation changes to the Christchurch region, as a result of the earthquakes have caused implications for future hazards. Coastal and river hazards have now been exacerbated in particular areas and current assessments and monitoring of these hazards will now have to be re-done with the inclusion of new base line monitoring levels. Flooding, sea level rise and tsunami are the three main hazards that were addressed in the interviews. Coastal and river flooding, sea level rise and tsunami hazards are thought to have been exacerbated in areas with lower evaluation, particularly in the northern part of Christchurch and the northern part of the Avon Heathcote Estuary. Exacerbating coastal erosion was another issue that arose from the interviews as well as a heightened risk of landslides and rock falls on the Port Hills area. In conclusion this chapter has highlighted that the coasts and rivers of Christchurch have been areas most susceptible to damage during the Canterbury earthquake sequence. The impacts were both significant at the time of the quakes but will continue to be significant with regard to long term changes to coastal and river hazards. These impacts and hazards will form an important component of the long term recovery and rebuild of Christchurch city.

5 CHAPTER FIVE: RESULTS AND DISCUSSION CHRISTCHURCH'S RECOVERY AND REBUILD: PROGRESS FOLLOWING THE CANTERBURY EARTHQUAKE SEQUENCE

5.1 Introduction

The results and discussion in this chapter will present the prevailing interview themes which centre on the recovery and rebuild of Christchurch following the Canterbury earthquake sequence. The themes will discuss the current progress of the rebuild and patterns of recovery that have occurred in the last year and a half following the February 2011 earthquake. Discussions on the progress of re-zoning and the patterns of recovery will also draw focus to coastal and river environments within Christchurch. This will be done in order to determine whether or not coastal and river areas are more disadvantaged in terms of their ability to recover in a timely manner after a hazard event has occurred. The following discussion and conclusion chapters will ultimately aim to discuss the lessons that can be learnt as a result of this research and, in particular, to derive lessons for coastal and river cities in New Zealand and worldwide. The last two research questions described in Chapter Two lead the discussions in this chapter:

1. What recovery progress can be observed in Christchurch and how does this progress influence the city's resilience to hazards?
2. What lessons can be learned from the Canterbury earthquake sequence that is important for other coastal cities in New Zealand and worldwide?

The analytical approach in this chapter has the same structure as Chapter Four. First, the themes originating from the interview responses are named and described. As addressed in Chapter Two, themes are repeated patterns of the same meaning, which allow for further discussion related to what the theme represents. After the description, the theme will then be backed up by quotes from the experts. These quotes will then be backed up by or compared to background literature, photos and maps to observe whether or not the experts' knowledge is in consensus or has variance with this information. The themes will then be related back to the hypothesis and objectives of this study in order to understand whether the theme supports the hypothesis or creates avenues for further research.

This chapter first starts by presenting the theme relating to the overall damages and cost of the Canterbury earthquake sequence to date. This theme aims to discuss the damages and costs to the CBD, residential areas and infrastructure. The next part of the chapter will present and discuss the progress of recovery that has occurred so far, within Christchurch. This section will have a focus on land zoning decisions including what the categories are, what defines them and any associated problems with the land zoning decisions. The following section focuses on the legislation changes that have occurred following the earthquake events and also looks at what legislation still possibly need updating. This theme is important as regional and national level documents govern the way in which natural hazards are managed and any changes post the earthquake event will be significant for the management of future natural hazards. All the themes covered in this chapter will be related to significance to coastal and river environments in particular.

Understanding the extent and scale of the Canterbury earthquake sequence is a central component of the next section of this chapter. One of the main themes arising from the interview responses was the concept of extent and scale and that the extent and scale of the February earthquake went beyond the anticipated worst case scenario for an earthquake event in Christchurch. The last section aims to discuss people's awareness of natural hazards in Christchurch both before the earthquakes and after the earthquakes including looking at the difference in awareness between the public and experts. This section will also focus on the lessons that have been learnt as a result of the earthquake sequence for both Christchurch city and New Zealand. As a result of any natural disaster it is imperative that lessons are learnt as a result of the disaster event. These lessons enable both the public and those in governing positions to make changes and decisions that will ensure future events are not as disastrous as the one that had occurred.

A key point addressed in this chapter is that the February 2011 earthquake was a natural disaster, one of the worst in New Zealand's history. Christchurch city will now need to build up physical resilience to natural hazards if it is to avoid this scale of disaster in the future. The previous chapter looked at the influence of the earthquakes on the coastal and river side environments, which include effects on both the man made environment but also the natural environment. This chapter aims to discuss the impacts of the earthquake beyond physical effects to the coastal and river environments and discuss the earthquake impacts at all levels. This allows for a more comprehensive understanding of the lessons that can be learnt as a result of the earthquake events and, in this light, examines some of the decisions that have already been made during the recovery process. There is general agreement in Canterbury that the recovery of the city needs to build in greater resilience in the physical environment to both seismic hazards and other natural hazards. This chapter therefore includes a discussion on evaluating the effect on the city's future resilience with a focus on the physical environment through the decisions making process so far.

5.2 Damages and Costs of the Canterbury Earthquake

As well as coastal and river areas being subject to liquefaction, lateral spreading, flooding and rock falls, issues also arose concerning damage to infrastructure and essential lifelines. This section aims to describe the damages to the built environment of Christchurch and to present the estimated costs of these damages. Whether or not these damages and costs can be attributed significantly to coastal and river characteristics will also be discussed in this chapter. 'Damages' was a theme that resulted from the interviews and mainly centred on land damage and infrastructure damage. The damage to residential and commercial buildings, roads, bridges and lifeline networks including power, water, and waste water as a result of the Canterbury earthquakes was extensive.

The September 4th earthquake largely impacted wider Canterbury, considerably in the coastal satellite towns of Pines Beach, Kairaki and Brooklands and in the riverside towns of Kaiapoi and Halswell. Pines Beach and Kairaki are small beach side communities located to the north of the Waimakariri river mouth on, just behind the sand dunes of Pegasus Bay. The satellite township of Kaiapoi is located north of Christchurch along the banks of the Kaiapoi River which is a tributary of the Waimakariri River. These three areas suffered significant land damage as a result of the September 2010 earthquake and to date 1010 residential properties have been red zoned, approximately 80 in Pines Beach, over 900 in Kaiapoi and every one of the Kairaki residences (CERA, 2012) (Figure 5.1).

To a large extent the damage suffered in Kaiapoi can be attributed to its location to the Kaiapoi and Waimakariri River. Kaiapoi Township lies on reclaimed land which lies on old channels of the Waimakariri River, which have been cut off from the river since the mid 1850s. These old river bed channels correlate well with many areas that suffered significant liquefaction damage with substantial lateral spreading and sad boils. These caused significant damage to stop banks and other structures along the current river path of the Waimakariri with fissures up to 2 m deep and 2 m wide. Much of the residential housing was damaged by lateral spreading with displacement offsets up to 3 m parallel to old channel beds that have aggraded over time. In areas that were free from lateral spreading, the houses were damaged by the ejection of liquefied material that reached 400 mm deep in places which caused settlement and tilting of properties (Wotherspoon *et al.* 2012).

Brooklands is a community located on the southern side of the Waimakariri River and just west of the Brooklands Lagoon which is a part of the Waimakariri River Mouth. This community also suffered significant land damage as a result of the Darfield earthquake and to date has approximately 417 red zoned properties (CERA, 2012). The areas of Pines Beach, Kairaki and Brooklands are residential areas that have been built upon old sand dunes, consequently making the soils there highly susceptible to liquefaction. Thus liquefaction was the main cause of land damage in these areas as the fine silts and sands beneath the ground liquefied during the Darfield earthquake and as a result saw a large number of homes North of Christchurch red zoned (figure 5.1). The town of Halswell, located along the banks of the Halswell River in the south west of Christchurch city also suffered effects due to liquefaction and lateral spreading, yet on a slightly smaller scale than that of the towns in the north. Fortunately land damage in this area has been deemed economically viable for land repair and accordingly has been zoned green, which means that repair and development within this area can go ahead.

The Christchurch CBD suffered extensive structural and infrastructural damage as a result of the February earthquake. As of the 22nd of March 2011 the first assessments of the entire city had been undertaken in order to establish building safety, with each categorised according to indicator tag system, red, yellow or green (Table 5.1). Many buildings within the CBD withstood the effects of the earthquake from a structural perspective but were considered unusable because of damage to facades, ceilings, partitions and contents, and the risk from falling panels, glass and masonry that could cause injury or death (Baird *et al.* 2011). The entire CBD within the ‘four avenues’ (Bealey Ave, Morehouse Ave, Deans Ave and Fitzgerald Ave) was cordoned off and heavily guarded to protect people from the damaged buildings and prevent looting, The CBD red zoned cordon has also been significantly reduced to date (Figure 5.4). Because initial tagging only gave a preliminary assessment of building safety, further assessments were undertaken during the remainder of 2011. To date (October 2012) More than 700 buildings within the Christchurch CBD have been or are still to be demolished, because they are either unsafe or cannot be economically repaired (Figure 5.5).

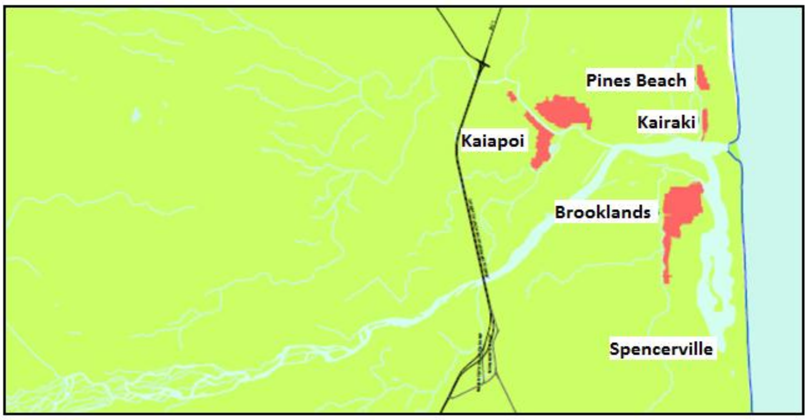
Due to the scale and extent of land damage arising from the earthquakes, broad geotechnical land damage assessments have been undertaken. These assessments have given a clear picture of how the land has changed in the worst affected residential suburbs of Christchurch. Land damage has be divided into two types: 1) land damage on flat land and 2) land damage on the hills. On the flat, there are seven physical land damage categories: these are lateral spreading, land cracking, undulations, ponding, local settlement, groundwater springs and inundation by sand and silt. In addition to this physical damage, the land has also undergone other changes. Over much of the wider Christchurch area land is now lower, higher, or in a different place to where it was before the earthquakes. The fact that the land has changed does not mean, in itself, that it is damaged. In the hills, there are three damage categories: these are rock fall, large-scale land movement (such as cliff collapse and major inundation), and small-scale land movement and retaining wall failures. Much of the physical land damage in the Port Hills is ground cracking which are similar to the cracks on the flat (Tonkin and Taylor Land Report, 2012). The below quote from expert Shamus Wallace also notes the main land damage observed in Christchurch.

"Eastern suburbs had significant structural and land damage, particularly Bexley, Avonside and Dallington. [Tonkin and Taylor] conducted observational land damage assessments which included observed liquefaction, lateral spreading, ponding, groundwater springs, undulating land, retaining wall failures, rock falls and slumping, in order to help EQC identify areas of damage" (Shamus Wallace- 27/8/2012).

Table 5.1: Table showing the number and percentage of buildings in the Christchurch CBD that were categorised as red, yellow or green following the February earthquake (Source: Stevenson, 2011:3)

1st Assessment building tags	Number	Percentage
Red - Unsafe - do not enter or occupy	826	23%
Yellow - Restricted use- no entry except on essential business. No public entry or residential occupation	862	24%
Safe – no restriction on use or occupancy	1933	53%

After the February 22nd earthquake more widespread and significant damage was suffered in coastal and river suburbs compared to the September 4th earthquake. In total after the February 22nd earthquake 7256 residential homes have been red zoned, both within Christchurch and wider Canterbury. Areas most affected by liquefaction and lateral spreading were consequently red zoned, this includes the suburbs surrounding the Avon River, the Avon Heathcote Estuary, the Kaiapoi River, the Waimakariri River Mouth and Brooklands Lagoon (Figure 5.1).



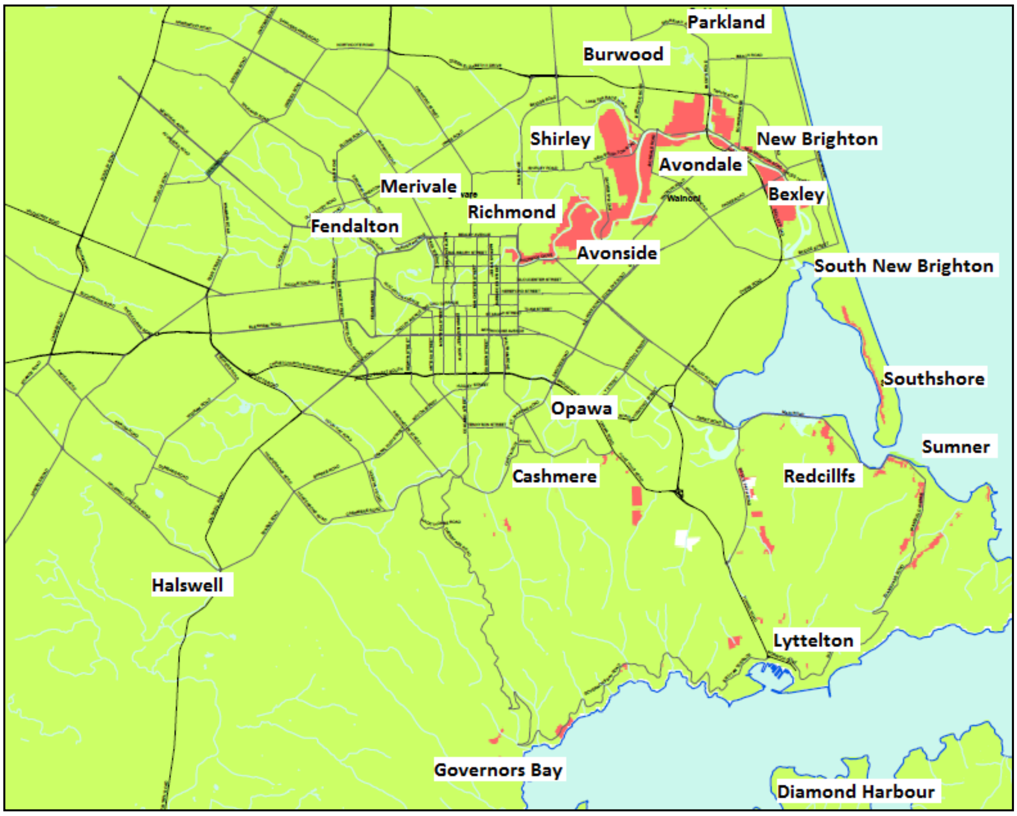


Figure 5.1: The top map shows the red zones in the northern Christchurch and Waimakariri District suburbs and the bottom map shows the red zones in Christchurch (Source: CERA, 2012)

The suburbs surrounding the Avon River include: Richmond, Dallington, Avonside, Avondale, Bexley, New Brighton and surrounding the estuary is the suburb of Southshore. As explained in Chapter Three and Four, the areas surrounding the Avon River and the Avon Heathcote Estuary are built upon soils that are highly susceptible to liquefaction as they are predominantly made up of sands, silts, peats and gravels. This meant that liquefaction induced lateral spreading caused settlement, tilting, flooding of thousands of homes and severe damage to infrastructure along the length of the Avon River (Figure 5.2).

Figure 5.2: Photos showing the damage made to structures around the Avon River as a result of lateral spreading (Source: Diane Dixey, February 2011)

Many thousands of residential homes were damaged with the worst damage observed in the eastern suburbs due to liquefaction and lateral spreading while high levels of vertical and lateral shaking was responsible for housing damage in the hill suburbs (Buchanan *et al.* 2011). During the February earthquake up to 15 m of cliffs around Redcliffs failed along fractures and through intact rock during each shaking event due to very high vertical and horizontal accelerations. This lead to hundreds of houses being severely damaged, requiring evacuation, and approximately 100 houses unlikely to be reoccupied both at the cliff top and base (Bell, 2011). These failed cliff tops and cliff bases were predominantly coastal cliffs that are located along the coastline from Redcliffs to Sumner and damaged the main road that connects Sumner to the city (Figure 5.3). After the February earthquake, roads and bridges in to and out of coastal and riverside areas were damaged. This hampered evacuations, rescue and recovery efforts and also ongoing occupation of these areas. It appears that coastal and river infrastructure are vulnerable to earthquake hazard events because they lack inbuilt redundancy, which can cause access and exit disruptions if there is only one or two routes available to any one location.

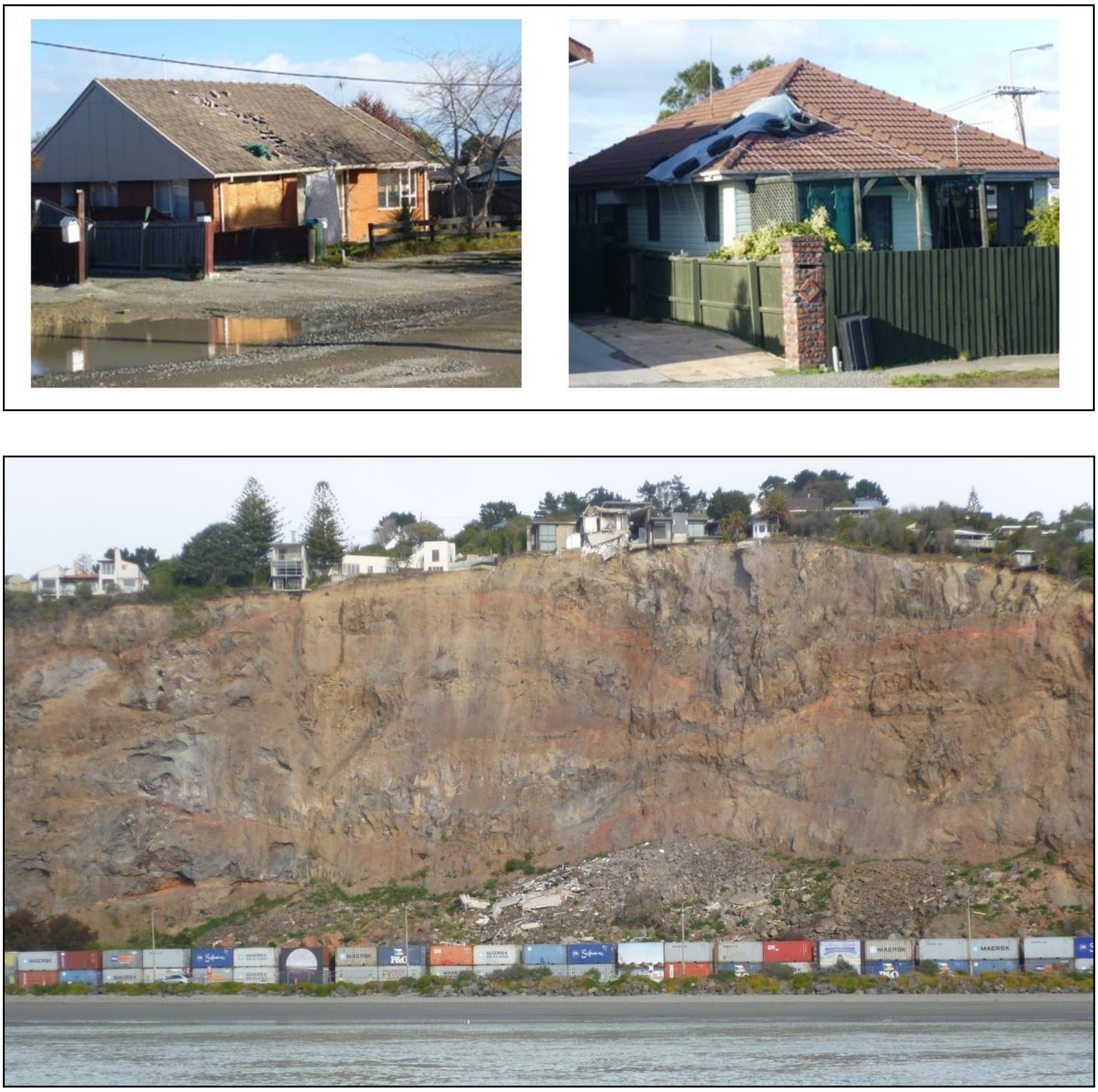


Figure 5.3: Top photos show housing damage in Bexley and New Brighton. Bottom shows housing damage around coastal cliffs and the container wall lining the main road to protect the vehicles from falling rocks (June, 2012)

This is particularly important in Southshore, Lyttelton and Sumner where access is limited to only two roads. After the February earthquake there was intense traffic congestion into and out of Sumner and Southshore due to damaged roads and bridges. Clifton Hill collapsed and threatened the seaward road linking Red Cliffs and Sumner to Christchurch city, requiring the use of ballasted shipping containers as a temporary catch fence (Giovinazzi *et al.* 2011) (Figure 5.3). The tunnel which allows motorists to access Lyttleton was also closed, which meant that the only road open to access Lyttelton was Dyers Pass, over the Port Hills. This road was also dangerous to use at the time as land slips and rock falls posed a serious threat to vehicles and people commuting on foot. Overall an estimated 600 km of roads were severely damaged as a result of the 2010 and 2010 earthquakes (CERA, 2012).

Power, water and sewage systems were severely damaged in both the hill suburbs and the eastern suburbs. The large ground deformation induced by the 22nd February earthquake badly affected roads, bridges and underground cable networks, inducing major power and water outages and loss of functionality to the power and water distribution system (Figure 5.7). Of the 66 kV underground cable network, 50% of cables were damaged and all major 66 kV cables, supplying Dallington and Brighton zone substations (north-east area of Christchurch) were damaged beyond repair and had to be abandoned. A total of more than 1000 faults were identified and repaired at 31st August 2011 (Orion Media release 31st August 2011). Despite the severe physical impact of the February earthquake on the Orion distribution and sub-transmission network, Orion was able to restore the power to about 50% of occupied households on the day of the event, 75% after 2 days, 90% within 10 days and 98% after 2 weeks (Giovinazzi *et al.* 2011).

After the February earthquake, the damage to sewer pipes meant that sewage was discharged directly to rivers, estuaries and beaches resulting in swimming and recreation closures for around 12 months. The input of sewage into rivers and the estuary had significant biological implications, which meant that fishing and swimming bans was in place for more than a year following the February event. River bans or warning signs about unsafe water are still occurring in places at present due to damage to pipes being repaired or used in reconstruction efforts. Furthermore these earthquakes have caused changes in the coastal plain of Pegasus Bay causing disruptions in scientific baselines which as indicated in Chapter Four, will have implications for previous measurements of coastal hazards including sea level rise, tsunami and flooding.

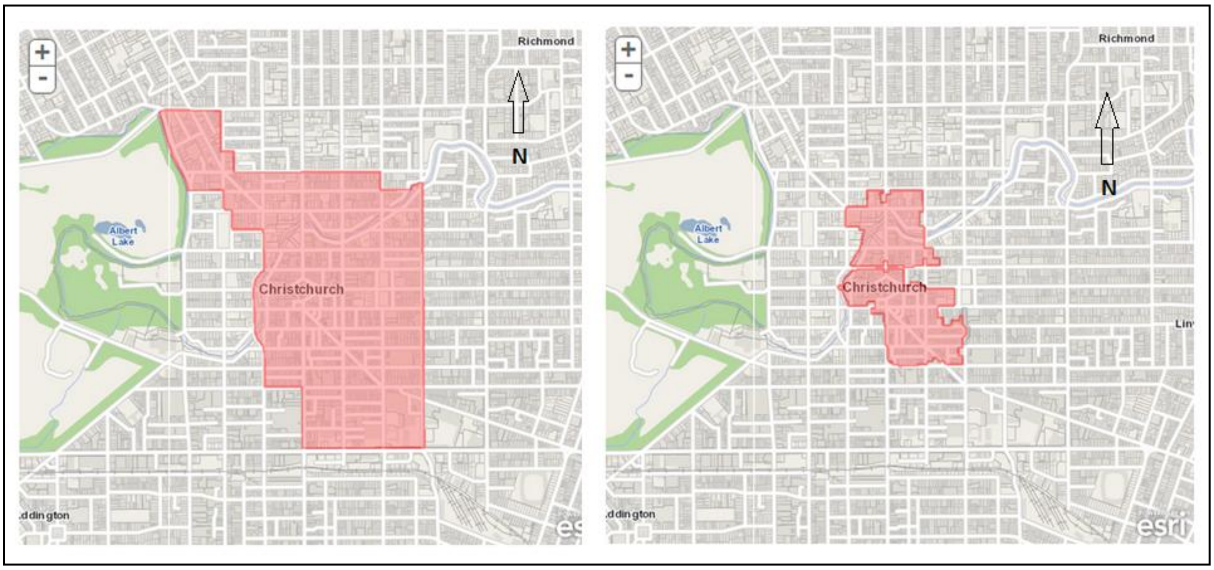


Figure 5.4: Maps showing the reduction in the CBD cordon from March 2011 to October 2012 (Source: CERA, 2012)

Figure 5.5: Photos showing the areas of the CBD that are still cordoned off and buildings that are have been demolished and that are destined still for demolition (October 2012).

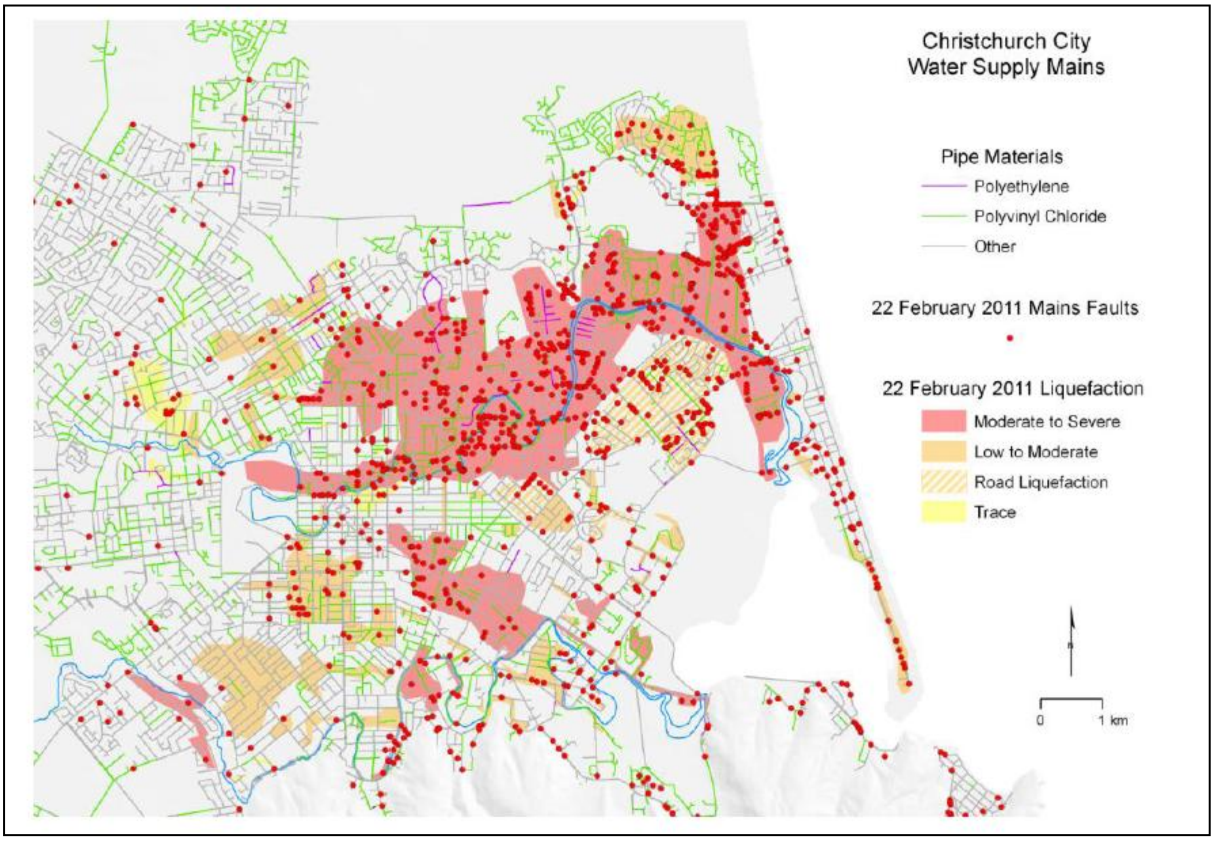


Figure 5.6: Map showing the location of water mains pipe network and location of breaks caused by the February 22nd earthquake. Coloured lines indicate pipe material; coloured areas indicate liquefaction severity. (Source: Cubrinovski et al. 2011: 223)

Following the Darfield event there was 604 water pipeline repairs and following the February event there were 1645 and 406 following the June events. 36,000 water and wastewater service requests were received and addressed by Christchurch City Council in the 5 months following the earthquake (Figure 5.6). Approximately, 50% of the city was without water for the first days following the earthquake and more than a third of households were without water for over a week. A month on from 22 February 2011, over 95% of homes (outside of the cordoned CBD) had water, however a "boil order" was in-place for over six weeks for most of the city due to potential contamination caused by severe damage to the wastewater system. Chlorination, which was not used pre-earthquake, remains a requirement to ensure water is disinfected. Water conservation orders are in place as a result of damages to key water reservoirs and the loss of many groundwater pumping wells; all related to geotechnical problems (Charman and Billings, 2011). The below quote from expert Sonia Giovinazzi underpins the main infrastructure damage as a result of the earthquake sequence. She notes that damage to infrastructure was a result of land damage caused by liquefaction.

"There was damage to underground cables. New Brighton- Dallington cable damage beyond repair and had to build over head cables to supplement power. Treatment plants were affected. Orion did well with building reinforced structures on the ground. Over head lines were not affected significantly. Some piles were crooked but did not affect functionality. Land damage caused by liquefaction caused damage to lifelines, but there were materials that performed well even with land damage present. Gas system was new, and performed well whereas the water system was old, and had not been upgraded due to expense" (Dr Sonia Giovinazzi – 10/8/2012).

Figure 5.7: Top photos show the damage that occurred to bridges and their pipelines in eastern Christchurch. Temporary pipelines had to be put on the surface of the broken bridge. The bottom photos show damages to roads (June, 2012)

The cost of the Canterbury earthquakes in 2010 and 2011 is estimated to exceed $20 billion (figure 5.8) and the earthquakes events had reduced New Zealand's GDP by an estimated 1.5 per cent in 2011. The Crown will contribute more than $8.8 billion to the recovery in the period to 2015. It has allocated $5.5 billion of core expenditure through a notional fund, the

Canterbury Earthquake Recovery Fund (CERF). Another $3.3 billion is estimated to be required for the State-owned enterprise and Crown entity sectors. Local government is also contributing financially to the recovery by sharing the cost of repairing and reinstating water, sewerage, road and transport infrastructure and other council facilities. No one agency or group will be able to achieve recovery alone. Collaboration is essential to connect those who have a role in recovery, including those in the government, Iwi, business, cultural and other nongovernment sectors (Christchurch Recovery Strategy, 2012). As a result of background research and interview data it can be established that damage to homes, infrastructure and lifelines was predominantly in the CBD and in the eastern suburbs, as well as pockets of coastal and river locations north of Christchurch. Below is a quote from expert Matthew Hughes who reiterates this point:

"In eastern Christchurch there was liquefaction, property damage and infrastructure damage. In western Christchurch there was damage to water and sewage systems but not as widespread as in the east" (Dr Matthew Hughes – 6/8/2012).

The CBD and eastern areas were damaged mainly due to liquefaction and lateral spreading which occurred because of the sediments and high water tables that are found beneath the area. As explained in Chapter Four these areas are predominantly past and present coastal and river environments and it is this feature that has made it possible for liquefaction and lateral spreading to occur. The other parts of Christchurch that suffered significant damage due to rock falls was the coastal cliffs around Red Cliffs and Sumner and the Hill suburbs above. As such, the damages and costs associated with the earthquakes can be attributed to the prevalence of coastal and river environments in Christchurch.

Sector	Residential	Commercial	Infrastructure	Land remediation	Total
Recovery cost (billions)	$10.5B	$4B	$3B	$2.5B	**$20B**

Figure 5.8: Estimated cost of the Canterbury Rebuild (Source: CERA, 2012)

This theme assists in supporting the hypothesis of this study as the vulnerability of coastal and river environments to seismic hazards are again highlighted through damage to infrastructure and subsequent costs. Because there is a lack of inbuilt redundancy in roads in coastal areas they are more vulnerable to hazard events in terms of evacuation and rescue efforts. The water, power and sewage networks were mostly affected in eastern areas particularly in the suburbs close to rivers and the coast indicating that these systems are particularly vulnerable in coastal and river areas because of the sediments they are built within. Because there was a failure in the sewage system this meant that sewage was released into rivers and beaches. The biological and recreational impact of this was a significant outcome of the February earthquake and also highlights the vulnerability of rivers and coasts to negative effects associated with damage to human made systems, as a result of seismic events.

5.3 Progress of Recovery and Zoning Decisions

The interview data revealed that 'zoning' was a common theme discussed among the experts. Land zoning decisions have formed an important component of the recovery and rebuild process of Christchurch city. Decisions regarding the land's condition post earthquakes have to be made to make sure that the city does not rebuild back the way it was and aim to improve building standards. Zoning is primarily a plan for where it is appropriate to rebuild and categorising appropriate land into certain zones that requires a certain building foundation.

The first part of this section will briefly discuss the initial emergency response that transpired after the 22nd of February struck. It is important to cover the emergency response phase of recovery before discussing the recovery progress and zoning decisions because it is when lives are saved and injuries are minimised. The following parts of this section will focus on the recovery and rebuild phase which includes a discussion on the land damage assessments and the consequent land zone categories that have been decided on.

When the 22nd of February 2011 earthquake struck a state of national emergency was declared and stayed in force from 23rd of February 2011 until 30th April 2011. This was the first time in New Zealand's history that a state of national emergency had been declared as a result of a civil defence emergency (Tonkin and Taylor Land Report, 2012). The initial emergency response phase following the February earthquake focussed on the rescue and recovery of people and the treatment of the injured, clearing people away from unsafe areas and extinguishing any building fires. This phase also had an emphasis on meeting people's basic needs (water, power, and food) and demolishing unsafe buildings.

The emergency phase was aided by emergency teams from both across New Zealand and from international countries. The army was involved in keeping the city secure and safe for people and preventing looting within the CBD. Donations nationally and internationally to the Red Cross and other charities enabled the organisations to help those in need. Charities helped those who didn't have water or power or had lost their homes within the city. The Canterbury University Student Volunteer Army (SVA) was first organised after the September earthquake and was supported by initially 2500 students who volunteered to help clear the city of liquefaction and assist charities with their work. After the September earthquake the SVA cleared 65,000 tonnes of liquefaction from roads and homes and after the February earthquake they managed to clear 360,000 tonnes (Student Volunteer Army, 2012). Overall more than 500,000 tonnes of liquefaction was removed from the city (CERA, 2012). The number of people involved in the emergency recovery efforts with Christchurch, New Zealand and internationally was a remarkable feature. The efforts and time put in to helping people and helping the city to get back on its feet is a testament to hard work of emergency services and the hard work of caring volunteers, businesses and organisations.

After the emergency phase of recovery the phase of rebuilding begins. The first part of the rebuilding phase began with assessments of the land and buildings in the residential areas and the demolition of buildings within the CBD. Bringing down damaged buildings and opening the CBD back up for the public was a priority of the recovery process. A highlight within this progress of recovery was the opening of the Cashel Street Container Mall which highlighted the first step in revitalising Christchurch's CBD and welcoming the public back in (Figure 5.9).

In the residential areas, progress of recovery began when EQC commissioned geotechnical ground investigations for the suburbs most affected by land damage, following the earthquake on September 4th 2010. Engineering company: Tonkin and Taylor, conducted broad scale investigations on behalf of EQC within suburbs in Christchurch city, and Waimakariri and Selwyn districts. This included subsurface (below ground) site investigations and factual reporting for the suburbs most affected by liquefaction-induced land damage (Tonkin and Taylor Land Report, 2012).

Figure 5.9: Photos on the top shows the clearing of the buildings and land within the CBD in preparation for re-development and the photos on the bottom show what the Re-start container mall on Cashel street looks like (October 2012)

These investigations included the following:

a) cone penetration testing (CPT) - gives a profile of soil strength

b) machine boreholes - gives a profile of soil types

c) geophysical testing - looks at soil stiffness and density

d) groundwater observations - assesses groundwater levels

e) laboratory testing - analyses soil from the boreholes

From these land assessments the areas of Christchurch and surrounding districts have been divided into either red zones or green zones (Figure 5.1). Land in the green zone has been divided into technical categories which define how the land is expected to perform in future significant earthquakes with a magnitude greater than Mw 6.0 and describes the foundation systems most likely to be required in the corresponding areas (Table 5.2; Figure 5.10). Properties within the green zones categories can be repaired on an individual site basis and do not require area wide land works and the infrastructure is not as badly damaged. The land zoning categories had to be prepared because there had never been a natural disaster in New Zealand that had caused this much land damage as a result of land level changes, land settlement, liquefaction and lateral spreading. Zoning of the land was the most appropriate way to assess the land at such a broad scale.

"There is a huge amount of work going into classifying land into the technical categories and coming up with foundations suitable for dwellings specifically for those categories" (Graham Harrington –30/8/2012).

As this is an area wide classification, site specific geotechnical work is required to determine the actual foundations required for each house in Technical category 3 areas. The below quotes from the experts identify the information that was considered when defining red zones and categories within the green zone. They identify that land damage from liquefaction and lateral spreading is a main determinant of red zoned areas and also the economic viability of rebuilding the infrastructure in those areas.

The first quote below shows that flooding risk was also considered in the determination of red zone areas. This quote notes also that technical category 3 (blue) is the most vulnerable green zoned category susceptible to earthquake associated land damage and is located closest to rivers.

"So as far as the rebuild goes liquefaction and lateral spreading risk are being incorporated into the land use decisions. CERA in their initial decisions to spatially define the red zones that will be abandoned and that will no longer have maintenance in these areas were mainly due to liquefaction and lateral spreading risk but also aspects of local flooding have played into these decisions. Land zoning categories specify housing design and foundation design that are based upon vulnerability to liquefaction and lateral spreading. Technical categories 3 are those that are located closest to river, liquefiable sediments and land prone to lateral spreading" (Dr Matthew Hughes- 6/8/2012).

"Technical categories that have been defined by CERA do definitely take into account ground conditions such as water table depth. The red zones are based on areas that are just not worth rebuilding on. Believe that it is the infrastructure that is being considered more.

Wherever you build you can build decent foundations but it's no good to build these foundations if your sewage pipes are going to break every time, which is not good for people or the environment" (Dr Marion Irwin – 30/8/2012).

Table 5.2: Green zone land categories used to establish future land damage and foundations required for rebuilds.

Green zone category	Future land damage	Foundations required
TC1 (grey)	Future land damage from liquefaction is unlikely	Foundation systems can use standard foundations for concrete slabs or timber floors
TC2 (yellow)	Minor to moderate land damage from liquefaction is possible in future significant earthquakes	Foundation systems can use standard timber piled foundations for houses with lightweight cladding and roofing and suspended timber floors or enhanced concrete foundations
TC3 (blue)	Moderate to significant land damage from liquefaction is possible in future large earthquakes.	Site-specific geotechnical investigation and specific engineering foundation design is required.

Red zones are land that has been so badly damaged that a rebuild is unlikely for a considerable period of time. The land has mainly sunk and been affected by lateral spreading by several meters in places. Houses can be designed to withstand shaking and land settlement but they cannot be designed to withstand lateral spreading. The difference between the red zones and those areas zoned green is that the land in the red zones would require area wide works. It would need to be treated like a new subdivision; it would need to be completely cleared with large scale works, which would cause huge disruptions to communities over a long period of time. Houses in the red zone are also uneconomical to repair and the infrastructure would need to be completely rebuilt in those areas not just repaired in places. The below quote indicates that it was not only land damage that was considered when defining red zones, the long term disruption that a rebuild in the red zone would have on people's livelihoods was also a determining factor.

"Misconception that red zoning was based on 'bad' land but more on the practicality of rebuilding in the area, as there would be significant disruptions to people's normal day to day lives. More a case of red zones being inappropriate for rebuilding in terms of cost and livelihoods than it is a case of red zones being bad in terms of land damage and seismic hazard risk" (Shamus Wallace – 27/8/2012).

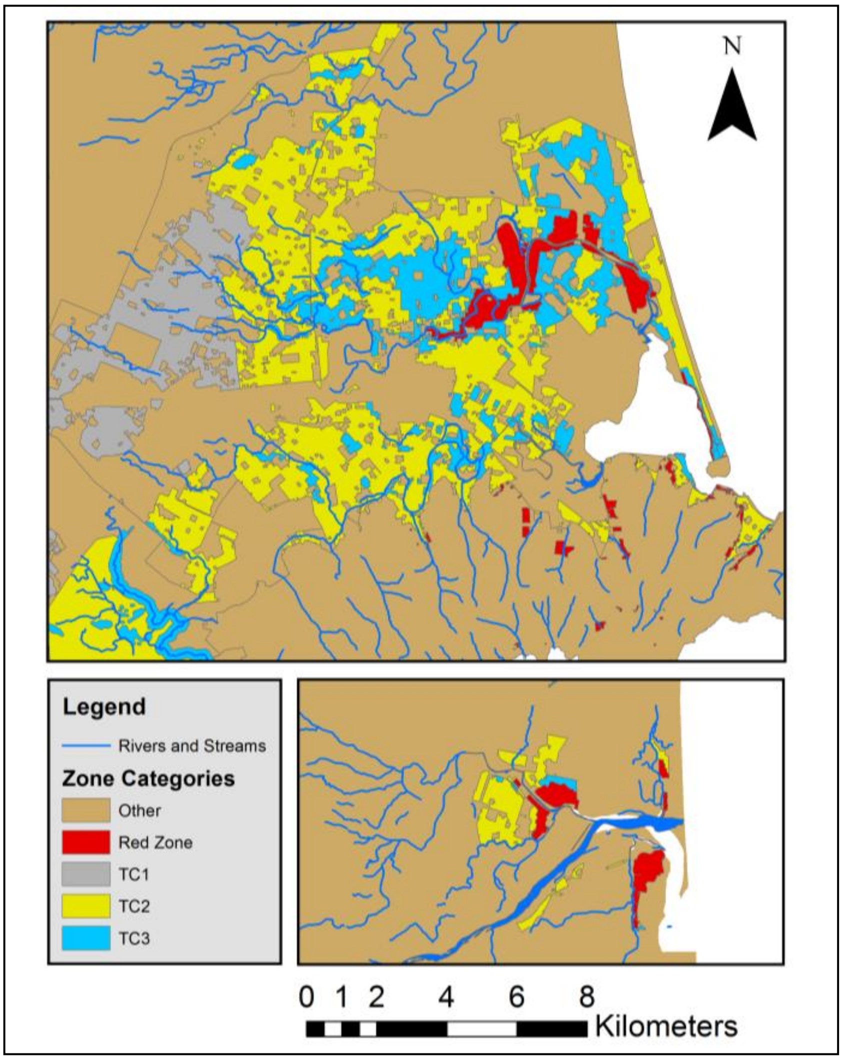


Figure 5.10: Top map shows the distribution of the technical categories of the green zone (Grey, yellow and blue) and the red zone in Christchurch. The bottom inset shows the red zones in Kaiapoi, Brooklands and Pines Beach.

The zoning of land and defining of categories has been a long process for many residents in Christchurch and the last decisions were finally made in October 2012, 1 year and 8 months after the February earthquake. In October 2012, 6090 out of 7860 red zoned property owners had signed agreements with the crown to sell their land. 4775 have already settled their sale with the Crown at a cost of approximately $947 million. Of the 7860 residential red zone properties (including bare, uninsured and commercial land), 7244 owners have submitted consent forms enabling the Crown to make an offer to purchase their properties.

The coastal areas of South New Brighton, Southshore, and the Port Hills residents were the last to find out what zone their land would be. There are now just eight Port Hill properties without a red or green designation, but a decision will be reached for those by the end of this month (October 2012). The fact that the coastal regions have had the longest wait time for decisions again highlights the vulnerability of these areas in terms of their ability to recover following an earthquake event. The pattern of timing for the land decisions centred first on deciding zones for the CBD and then focussing on the suburbs surrounding the CBD. It appeared that the focus for recovery was centred on the CBD, where most of the deconstruction and planning took place quickly and not centred on the suburbs where people are living and trying to make a new start.

In conjunction with the timely length of decisions regarding zoning there have also been issues as to whether the decisions determining green and red zones are appropriate and whether the decisions have been well informed by science. The two quotes below raise these questions regarding zoning decisions:

"It is certain that there is awareness now about where liquefaction occurs, but whether the picture on that is clear to people who are making decisions about land is uncertain. Those who are in the unenviable position of making design solutions right now about things such as infrastructures and properties, tend to be as careful as they can but are kind of making it up as they go a bit. There has been no comprehensive investigation of coastal land undertaken before these decisions have been made" (Emeritus Professor R.M. Kirk – 9/8/2012)

"There has not been transparency in how the zoning decision has been done. I do not know who supplied the data that the decisions were based on" (Dr Sonia Giovinazzi – 10/8/2012)

The re classifying of land for the rebuild of Christchurch has never been attempted before, in New Zealand. It is apparent that land decisions have been based on information from geological assessments and seismic assessments and to some extent flooding assessments. An issue that has become apparent as a result of this study is that land zoning decisions do not seem to have taken into consideration the changes that have occurred to other natural hazards in Christchurch following the earthquake sequence. Sea level rise is a pressing issue facing the world to date, because the rapid growth of coastal cities places growing demands on coastal resources and exposes more people to coastal hazards. Global climate change and, particularly sea level rise, will exacerbate all of these problems (Nicholls and Mimura, 1998). As such, it would seem essential that the rebuild process should be considering sea level rise in the land zoning decisions particularly around coastal and lower river areas. If areas by the coast have been green zoned, will they still be there in the next 100 years? The science today from the IPPC indicates these low lying coastal areas will most likely be inundated, so why make these areas green zones if in the long term when they should have been zoned red. These are questions that need to be raised to those people making decisions.

The ideas that came from discussing the ‘zoning’ theme support the hypothesis of this study. Land within Christchurch and surrounding districts have been divided into green zones and red zones. The red zones are areas that will no longer have lifeline facilities or any commercial and residential buildings, due to the land not being economically or socially viable for repair. This study aims to show that coastal and river areas are vulnerable to the impacts associated with earthquake events and Chapter Four has demonstrated that they are vulnerable to the physical hazards associated with earthquakes and suffered significant damage.

This chapter now highlights that coastal and river areas are also vulnerable to seismic hazards in terms of their lack of inbuilt redundancy in essential lifelines and their ability to recover in a timely manner. Figure 5.7 indicates the location of the red zones in Christchurch and the Waimakariri District. It shows that red zones are located mainly along the Avon River and the Kaiapoi River margins and along Brooklands Lagoon and around the Avon Heathcote Estuary. The TC3 land zone category is for properties that are most likely to suffer significant land damage as a result of another earthquake and this category is also located around these same coastal and river areas. Another factor indicating vulnerability is the slow rate of recovery around coasts and rivers. Around the coastline, there has been the longest waiting time for decisions to be made regarding the land. This means that recovery along the coastline could not proceed until these decisions were made.

Even though red zoning in coastal, estuarine and hill regions now means there is built up resilience to future hazards, there are still issues concerning the viability of re-building in open coastal locations, especially in terms of long term sea level rise. Because there has been a lack in transparency about how the zones were calculated exactly, it is hard to see if they really incorporate the risks of building around rivers and coasts. It only appears that there has been a consideration of the risks in river and estuarine areas but not so much for exposed coastal areas.

5.4 Extent and Scale of the Canterbury Earthquake Disaster

The extent and scale of damage as a result of the Canterbury earthquake sequence was a common theme addressed among the interviewed experts. In order to manage hazards, the expected risk of a hazard occurring needs to be scientifically informed and understood However, when a hazard event occurs the extent of the damage can be either lesser or greater than expected. This section will discuss whether there was an awareness of the risks associated with earthquake induced hazards in Christchurch such as liquefaction. These discussions will then lead into whether or not earthquake induced hazards occurred to a greater scale and extent to what was previously predicted.

The extent of damage as a result of a hazard can correlate with the extent to which an area was prepared for a hazard event. The more prepared a city is for a hazard, the more resilient the city should be towards the impacts of a hazard event. The Christchurch City Local Defence Emergency Management Arrangements Report published in 2008 recognised that the risk of an earthquake occurring in Christchurch was likely, due to the city's close proximity to tectonically active regions. The three main earthquake induced hazards recognised in this report was: earth deformation (ground surface rupture), earth shaking (liquefaction, land sliding, and ground cracking) and tsunami. The report also recognised that areas most susceptible to liquefaction are those with water saturated loose soils of sands and silts and that these materials underlay large parts of the eastern suburbs of Christchurch and the Heathcote River. Note that the risk of liquefaction around the Avon River was not mentioned in this report (Sinclair, 2008).

The report recognised that old masonry buildings built before the 1960s have not been designed to resist earthquakes and may be prone to damage if the earthquake event was relatively close and generated waves which were of predominantly short period. Because this report was based on the assumption that an earthquake would occur from a distant source fault, it appears that the risk to old unreinforced masonry buildings was set aside. Issues relating to earthquake risk in this report included how to most effectively mitigate the effects of ground shaking on buildings and structures and whether set development controls for works in an area particularly susceptible to liquefaction could be controlled more rigorously than areas of little or no risk (Sinclair, 2008).

The quote below indicates that the risk of liquefaction was well recognised within the scientific and management community, as a result of the published report: '*Risk and Realities: A multidisciplinary Approach to the Vulnerability of Lifelines to Natural Hazards*' prepared by the Christchurch Engineering Lifelines Group.

"I was involved in the Christchurch lifelines group study. The group drew attention to the seismic risk in Christchurch, admittedly more to an alpine fault rupture risk and they drew strong attention to the risk of liquefaction in Christchurch, they created maps and chapters were written about liquefaction. No council in Christchurch can say that they didn't have information about seismic risk or liquefaction, none what so ever. But we have a culture in Christchurch that simply discounts risk in favour of economic development. The argument is quite unsatisfactory as there can be economic development without putting areas at risk. It is about developing wisely; it does not have to be one or the other" (Emeritus Professor R.M. Kirk – 9/8/2012).

As addressed in Chapter Three, the report was published in 1997 and recognised three different earthquake scenarios affecting Christchurch that could produce strong shaking intensities of up to 8-9 Mm, with a return period of 150 years. Such an event would occur from either a moderately large to large earthquake in the Canterbury foothills, a very large earthquake on the Alpine Fault or an earthquake centred close to Christchurch or under Christchurch itself. The report did recognise that the likelihood of an earthquake near Christchurch was remote due to a lack of indications of surface fault ruptures in the Canterbury Plains or Banks Peninsula (Christchurch Engineering Lifelines Group, 1997). On the whole, this report prepared risk information based on an earthquake event that was far larger than the earthquakes that occurred in 2010 and 2011.

The report indicated that Christchurch is potentially at high risk from widespread liquefaction due to its location on a saturated, sand and silt rich prograding coastline. It provided maps indicating where liquefaction would be most prevalent in the occurrence of an earthquake and shows that liquefaction would mostly occur in eastern areas. The report also highlighted that damage from liquefaction induced lateral spreading is usually more extensive and serious than that from liquefaction settlement and noted that river banks are particularly susceptible giving a reference to the Avon River, Heathcote River and the Waimakariri River. The report also recognised that rock falls and landslides would be a significant hazard as a result of an earthquake, particularly along cliff faces and higher hill side areas.

The above information confirms that there was recognition of the potential risk of an earthquake occurring in Christchurch and the potential risk of earthquake associated hazards including liquefaction, lateral spreading and rock falls. However, it appears that this recognition was not able to aid in reducing the effects of these hazards when the Canterbury earthquake sequence began in 2010. The scale of damage as a result of liquefaction and lateral spreading exceeded the extent predicted by maps produced by Environment Canterbury. Environment Canterbury produced maps that showed which areas of Christchurch would suffer liquefaction and land damage and these maps was a very good indicator of liquefaction induced damage but the maps were significantly exceeded in observed liquefaction following the February earthquake. For example the maps in Figure 4.6 shows that liquefaction was predicted to occur along the lower lengths of the Avon River and throughout the eastern suburbs but the map in Figure 4.7 shows that more severe liquefaction occurred along the Avon River than previously expected.

The below quotes illustrate that there is consensus among the experts that the hazards associated with the February earthquake exceeded predicted expectations of damage. This is because, the scale and extent of damage from liquefaction, lateral spreading and rock falls was far greater than expected, even though the biggest earthquake was a smaller magnitude than the one predicted in the 1997 *'Risk and Realities'* report. The quotes also indicate that even though there was recognition of the potential risk of liquefaction, not much had been done to try and minimise this risk because the risk of an earthquake in Christchurch was so remote. One expert below also noted that there may have been a failure to communicate the risk of liquefaction to the public, because following the earthquake, the public was surprised by the liquefaction phenomenon and mostly had no idea about the risk.

"Experts knew about it [liquefaction] but the public probably did not. Politicians care more about what the public thinks more than what the experts think. The experts did not expect to need to worry about it because the return period for earthquakes was so long. But actually those soils could liquefy a lot easier than previously thought by experts" (Dr Marion Irwin – 30/8/2012).

"Learnt that you can expect things to happen and you can expect the worst but the scale of this disaster, how many people were affected, the area that was affected, you knew there were

susceptible areas but the scale went beyond the expectation of the worst case scenario" (Justin Cope – 30/8/2012).

To conclude, this section identifies that the risk of an earthquake and earthquake associated hazards in Christchurch had been recognised prior to the Canterbury earthquake sequence. However, this recognition did not lead to any action that may have reduced the scale and extent of damages observed as a result of the earthquakes and their associated hazards. Therefore the scale and extent of observed damage as a result of particularly the February earthquake went far beyond the predicted worst case scenario for an earthquake event. The experts highlight that the remote likelihood of a large earthquake occurring close to Christchurch was a predominant reason for why no action had been taken to reduce liquefaction potential in the eastern suburbs or comprehensively communicate the liquefaction risk to the people who live in susceptible areas.

This section is significant to this study as it highlights that cities are again vulnerable to hazards because of failures to take actions that could minimise hazard impacts including actions to communicate hazard risks to the public and limit development in susceptible areas. Community competence is a key concept discussed in literature, communities that promote hazard awareness and population capacities are those that are less susceptible to hazard events and actions taken to increase a community's awareness though advertisement and education are key to reducing vulnerability (Cutter *et al.* 2008). Economic actions taken to help reduce the impacts of future hazards include the adoption of mitigation strategies that aim to lessen the probability of failure, this involves adaptive responses to disasters that enables individuals and communities to avoid potential losses in the future, (Rose, 2004). These actions take the form of rebuilding more resilient homes and infrastructure.

The relationship between natural disasters, recovery and vulnerability reduction is becoming a key scientific, economic and political issues and it is now widely accepted that some natural disasters arise because of developmental processes which re-constitute vulnerability (Lynos, 2009). A main variable determining long term impacts of a disaster on a country is the country's capacity to rebuild infrastructure, examples in literature state that infrastructure resilience is dependent on the number of physical systems themselves available coupled with their dependence and interdependence on one another. The more tightly coupled and interconnected the infrastructure system the less resilience it exhibits (Cutter *et al.* 2008). Any action taken post a disaster event, which decreases the interdependency of infrastructure systems subsequently, increases resilience, as a disruption in one sector does not have to cause a disruption in another.

To conclude it is appropriate to highlight that it should be essential to try and minimise the risk of natural hazards in an urban areas, even when the risk of the hazard is minimal. What happened in Christchurch should hopefully serve as a learning opportunity for other cities in New Zealand and worldwide when considering their own risks to all hazards, not just earthquakes.

5.5 Legislation Changes

Discussions on possible legislation changes were another topic of interest obtained from the interview responses and consequently brought about the theme called 'legislation'. As a result of the catastrophic February earthquake it appeared poignant to review current legislation, which manages natural hazards and, in particular, the management of earthquake hazards. This theme discusses the possible changes to both regional and national level documents, which could be made or have been made in the light of the Canterbury earthquake sequence. Investigating and updating of governing documents is an important component of recovery after a natural disaster. Without making changes to documents that govern a city and the way it manages natural hazards it would not be possible to build future resilience to natural hazards. Through advancements in planning frameworks it is likely that further, more appropriate decisions would be made, with regard to a city's development and hazard management. This section will start with discussing changes to the Resource Management Act 1991 (RMA) and will end with a discussion of the possible changes or updates to the Ministry for the Environment's sea level rise document '*Coastal hazards and climate change: A guidance manual for local government in New Zealand'* and possible changes or updates to The New Zealand Coastal Policy Statement, 2010.

In October 2011, the Minister for the Environment established a Technical Advisory Group (TAG) to undertake a comprehensive review of the RMA (particularly section 6 and 7) in order to provide greater attention to managing the issue of natural hazards and noting issues arising from the Canterbury earthquake (Saunders and Beban, 2012). The TAG report provided recommendations into the reform process of the RMA with the overall aim to improve how natural hazards are managed through the RMA. The first quote below indicates that the issues concerning the RMA are mainly due to how it has been used rather than issues with what is missing within the document:

"Problems with the RMA: it has been claimed that failure to plan for the risk to land subject to liquefaction is the result of deficiencies in the RMA to recognise liquefaction when subdividing land. The RMA does in fact say you have to avoid remedy and mitigate adverse effects of any and all natural hazards. The Act is less to blame than the way it was used" (Emeritus Professor R.M. Kirk – 9/8/2012).

The above quote demonstrates that there has been inadequate use of the clauses that require hazards to be mitigated in the RMA, resulting in poor decisions concerning development in high risk areas. It appears that changes to the RMA is needed to clarify what needs to be addressed and regarded when considering the risk of natural hazards and developments. Section 6 and 7 of the RMA set out a series of "matters of national importance" which must be "recognised and provided for" and "other matters" to which "particular regard" is to be had by those making decisions under the Act. Currently these sections do not refer to the issue of natural hazards and thus the TAG report recommended that the Act be amended to more clearly allocate responsibility for natural hazard planning (TAG Report, 2012).

The report also makes recommendations to change Section 106 – A consent authority may refuse subdivision consent in certain circumstances. Currently the section advises that a subdivision consent may be refused if it considers that the land, and any subsequent use of the land or any structure is or is likely to accelerate, worsen, or result in material damage to the land, other land, or structure by erosion, falling debris, subsidence, slippage, or inundation from any source. This section did not include consequences from active faults, tsunami, or geothermal activity, and is inconsistent with the definition of a natural hazard. The TAG report recommends the following changes to Section 106:

- Section 106 to be amended to expressly include liquefaction and lateral spreading, along with any other consequences of the events included in the definition of "natural hazard" in s.2. The definition of a natural hazard expressed in the RMA is: Any atmospheric or earth or water related occurrence (including earthquake, tsunami, erosion, volcanic and geothermal activity, land slip, subsidence, sedimentation, wind, drought, fire or flooding) the action of which adversely effects human life, property or other aspects of the environment.

- Section 106 be amended to reflect the risk associated with any natural hazard, rather than the likelihood of the event.
- Section 106 be amended so that the consent authority must refuse consent if there will be a significant increase in the risk associated with any natural hazard. This is a stronger use of language, as it used to be that a consent authority may refuse consent instead of must refuse consent.

For further information regarding changes to the RMA see Appendix 4. The below quote addresses the changes made to the RMA and highlights why the changes have been made, when looking at past development mistakes. A main issue that arose as a result of the Canterbury earthquake was that of subdivisions. There were subdivisions that were granted consent, which probably should never have been granted in the first place due to the risk of land damage associated with earthquakes. There were many subdivisions in the Christchurch area and the Waimakariri district that suffered significant damage as a result of the earthquakes and were built on land that should not have been developed in the first place predominantly due to risk from natural hazards.

"The RMA is being looked at as well as the Building Act. Liquefaction is now being included in the RMA separately from earthquakes. The RMA is now looking at being more risk focussed rather than hazard focussed. There is also going to be sediment management sections that are going into local government acts... They are changing and it's because there have been places that have been developed that shouldn't have been developed and changing legislation allows for parties to say no to those developments" (Dr Marion Irwin 30/8/2012).

The following two quotes indicate changes that are being made to the Building Act 2004 in order to address the risk to buildings from natural hazards. Currently the Building Act recognises natural hazards that include erosion, debris falls, subsidence, inundation (flooding) and slippage but does not have regard to active faults, liquefaction, lateral spreading or tsunami. Also, the guidelines for flood risk need to be updated to ensure risk from flooding in areas of Christchurch that have undergone subsidence are mitigated against. These updates to the building code and designs are an important part of the recovery process. Both new commercial and residential buildings will need to be constructed in a way that gives them greater resilience to the impacts of natural hazards, not just seismic hazards but also hazards related to climate conditions, such as storms and flooding.

"The Building Act is looking at redefining building standard in terms of earthquake accelerations and intensities" (Dr Marion Irwin – 30/8/2012)

"There are Building code changes and DBH [Department of Building and Housing] Guideline updates. Flood risk maps need updating for houses to meet flooding requirements. New houses may need to be built higher to counter flood risk" (Shamus Wallace – 27/8/2012)

The following two quotes indicate potential changes to national level documents that may not have been considered at present. The first change discussed is the potential need to update the Ministry for the Environments Sea Level Rise documents and the second indicates the potential to update the New Zealand Coastal Policy Statement. The Ministry for the Environment Guidance Manual: Coastal Hazards and Climate Change propose a base amount of future sea level rise. For planning and decision timeframes out to the 2090s (2090–2099): a base estimate sea-level rise of 0.5 m relative to the 1980–1999 average will be used, along with an assessment of the potential consequences from a range of possible higher sea-level rise values. At the very least, all assessments will consider the consequences of a mean sea-level rise of at least 0.8 m relative to the 1980–1999 average (Ministry for the Environment, 2008). The below quote indicates issues arising from the Canterbury earthquakes with regard to these sea level rise predictions and indicates that there may need to be changes to planning levels for sea level rise in Christchurch given the changes to the land that has occurred.

"There are issues for hazard plans, natural hazard plans, national level documents. Ministry for the Environment documents on sea level change say to allow for 1 m sea level rise over the next century, but the earthquakes have caused the northern coastline of Pegasus Bay to go down half a meter which has added 200 years of sea level rise to the already known 22 cm rise that has already occurred over a matter of seconds. If you're going to plan for sea level rise in Christchurch you now need three different numbers to plan for, not one. You need one for where coastline has not changed, one for where the coast has uplifted and one for where the coast has subsided post the earthquakes" (Emeritus Professor R.M. Kirk – 9/8/2012).

The next quote below indicates that it may also be prudent to investigate national and regional coastal and river related documents to ensure that they have sufficient information and regard for all potential natural hazards. As described in Chapter One, the New Zealand Coastal Policy Statement does take into account natural coastal hazards but does not have regards for seismic hazards and evidence from the Canterbury earthquake sequence would indicate that seismicity is actually a coastal environmental hazard in New Zealand. The same issue can be said for legislation governing river environments such as the Conservation and Rivers Control Act 1941. It would seem prudent for an investigation into these documents to ensure risks from liquefaction and lateral spreading are identified and have regard for. This would seem particularly important when considering the amount of damage that the rivers in Christchurch city, the Waimakariri district and the Selwyn districts suffered.

"Wouldn't do any harm to change [Coastal] legislation to have regard for earthquake hazards. It is not something that has been considered generally in long term planning for coastal stability and in hind sight it would be a good idea to at least think through those consequences. It is a possibility that not many might have thought of yet" (Dr Murray Hicks – 23/8/2012).

This section has highlighted an important component of the recovery process following a natural disaster. It is imperative to investigate and update documents that govern the way in which natural hazards are managed in order to improve resilience within a city. If these investigations do not take place and changes are not addressed it would be likely that the same mistakes that made a city vulnerable to natural hazards in the first place, would be repeated. Experts R.M Kirk and Marion Irwin have indicated that developmental mistakes are re-occurring in certain areas of Christchurch. However, it is a positive sign that changes are being made to the Resource Management Act 1991 which is the main governing document of the management of land and hazards in New Zealand. However, this section has highlighted that there are potentially other documents including the Guidance manual for sea level rise and the New Zealand Coastal Policy Statement, 2010, that need to be investigated to ensure they are also leading the way to greater resilience. The updating of legislation is important for building awareness of natural hazards and increasing information about them and learning from past mistakes.

5.6 Awareness of Earthquake Risk and Lessons in Coastal and River Environments

Another common theme discussed among the interviewed experts was to do with the past development mistakes made in Christchurch and the following awareness and lessons that can now be learnt from these mistakes. As such, 'awareness and lessons' is the common interview theme presented in this section. In light of the Canterbury earthquake sequence it became apparent that some areas of Christchurch should not have been granted consent in the first place for new developments, even when consents were declined they were challenged through the environment court, which resulted in the granting of the consent in the end. This is because they were areas that suffered extensive land and structural damage as a result of the earthquakes and have consequently been red zoned. The first part of this section will focus on what development mistakes had been made in Christchurch and what issues following the earthquakes, are people now aware of. The second part of this section will focus on the possible lessons that have been learnt as a result of the earthquakes in Christchurch. There will also be a focus on how these lessons may be applicable to other cities in New Zealand and help enable a greater resilience to hazard events in the future.

The main issue discussed by the experts was that there was development of certain parts of Christchurch that possibly should not have been granted consent in the first place. They raise this issue because parts of Christchurch were extensively damaged by liquefaction induced lateral spreading and settlement due to the soils that these areas were built upon. Dr Marion Irwin stated that *"the development of the land in the past made liquefaction potential greater through the digging up of the land and making the sediments more unconsolidated"* and some of this development and digging up of the land would have occurred post the 1997 "*Risk and Realities*" report. An example of this would be the Seafield Lagoon subdivision in Brooklands and the southern end of the suburb of Bexley which comprised a new subdivision built in the 1990s called Pacific Park. This subdivision is now surrounded by controversy as to why developers were allowed to build there in the first place.

The Christchurch City Council backed the Pacific Park development in Bexley by changing the zoning to allow it and profited from the sale of part of the swamp to a developer. It seems that the 1990s was a market driven time and what developers wanted often outweighed other considerations such as natural hazard risk. The area is located on the fringes of the lower Avon River and right by what is known as the Bexley Wetlands. This means that the soils underneath this subdivision are completely water logged and comprised of sands, silts and peats making it extremely prone to liquefaction. Pacific Park suffered extensive damage during the February earthquake due to the ejection of liquefied material, land settlement and significant subsidence and has consequently been red zoned. The below two quotes reiterate the mistakes of building in certain parts of Christchurch:

"Areas are more vulnerable because they have been built on soft soils, and so of course liquefaction is an issue. Many areas should not have been developed at all" (Dr Sonia Giovinazzi –10/8/2012).

"If people had paid attention to hazards maps from the 1990s and took the risk seriously it's un-likely we would have had the level of housing damage that we have seen" (Dr Matthew *Hughes –6/8/2012).*

The Canterbury Royal Commission Report, Volume five, Section five, highlighted the fact that there had been unnecessary damage and costs sustained as a result of the development of land subject to a risk of liquefaction without duly considering that risk. It appears that there were mistakes made by people not adhering to advise presented by experts with regard to development in areas with a high risk of liquefaction and it is unfortunate that the awareness of these mistakes had to come about after the February earthquake disaster occurred. If people in management position had taken the risk seriously concerning earthquake hazards, when signing off new development projects, it is almost certain that the level of damage seen after the earthquakes might not have occurred.

Fortunately, awareness of these mistakes will mean that lessons can be learnt and that these mistakes with will not be able to take place again. This is based on the recommendations of the Canterbury Royal Commission Report which concluded that there should be better provision for the acknowledgement of earthquake and liquefaction risk in the various planning instruments that are made under the RMA (1991) and one way of minimising the failure of buildings in the future is to ensure that the land on which they are developed is suitable for the purpose. The quotes below indicates that Christchurch now has the opportunity to build the city back more appropriately, in a way that does not require the city to fight against the forces of nature which, in turn, increases the city's resilience to hazards.

"One of tiny upsides of all the damage that has occurred because of the earthquakes that we have the opportunity to now get some areas right that were previously wrong. By retiring those areas or converting them to uses that are not earthquake critical, that do not put life at risk, that do not put infrastructure at risk. Pull out of some areas that should not have been developed, for example the inner sides of the Brighton Spit. We have the opportunity now to say that we do not want to repeat this development mistake and speed up the process of it not ever being too late and think about the land and think about how it can be used better than it

was previously. Avoidance and prudence is needed when development occurs in these areas, you need to try to avoid a fight with nature" (Emeritus Professor R.M. Kirk – 9/8/2012).

"In some areas of Christchurch the development should never have occurred. But having built there now, they have the option to move or not and it looks like they are taking the option of not building back how they were but they are building back where they were" (Dr Marion Irwin –30/8/2012).

The above quote highlights that Christchurch and surrounding district councils now have the opportunity to either move areas out of hazardous locations or re-design buildings that can withstand the effects of future earthquake induced hazards. In Christchurch the movement of areas away from hazardous areas has happened with the establishment of red zones around the Avon River, the Avon Heathcote Estuary and parts of the Port Hills. The council has learnt a lesson with regard to building close to river edges, now fully understanding that they did 'know' from prior reports that rivers are highly susceptible to lateral spreading and this is why most of the lower Avon River has now been red zoned.

However, in some places in Christchurch, where it would seem to be appropriate to have red zones and movement of development away from high risk areas, the decision has been made to make these areas green. Fortunately, with rebuilding back on these areas that may be inappropriate to build back on, the building standards and designs will not be the same. They will be more advanced and be able to withstand future effects of earthquakes and earthquake induced hazards. This demonstrates that lessons have be learnt with regard to building designs and that there is now a recognition that building designs have to take into account land types and land susceptibility to earthquake hazards.

Unfortunately, even with new building standards there are some parts of Christchurch specifically around coastal areas that will still suffer from the effects of future coastal hazards such as storm surge and sea level rise and this issues appears to not have been fully considered in rebuild plans. This quote by Dr Sonia Giovinazzi reiterates this point: "*everything needs to be really integrated now, you can't just look at one thing, you need to have a multi hazard perspective in planning"*.

It is important to make sure that the lessons learnt in Christchurch can be made applicable to other cities in New Zealand, particularly those cities that are built along coastal margins with many river environments. Fortunately in Canterbury only 36% of the population live with 5 km of the coastline (Statistics New Zealand, 2006), where earthquake damage was most prominent. But if an earthquake was to hit the coastal cities of Nelson, Wellington or Auckland where the population living within 5 km of the coast is between 99-76% (Statistics New Zealand, 2006), a greater number of people would be affected. In some aspects the earthquake in Christchurch was a ‘best place scenario’, meaning that if the same or greater magnitude earthquake as the February earthquake was to have happened in another coastal city in New Zealand such as Wellington, the effects of that earthquake would have been much more significant than observed in Christchurch due to a greater number of people and CBD located closer to the coast.

The earthquake events in Christchurch have created greater public awareness about the phenomenon of liquefaction and the damage that it can have. The Canterbury earthquake sequence has hopefully brought awareness for other cities in New Zealand about the risk of all earthquake induced hazards, so that plans can be made to help minimise these risks in the future. This is important because *“Seismic activity is a serious hazard in New Zealand and some of the serious consequences are coastal. The kind of thing that has happened in Christchurch has the potential to happen in all eastern coastal cities in New Zealand” (Emeritus Professor R.M. Kirk – 9/8/2012).*

This section has highlighted that an awareness and learning of mistakes and lessons is an important step in the recovery process of a city following a hazard event. Christchurch city had a number of development mistakes that led to extensive damage during the earthquake sequence. Being aware of these development mistakes will hopefully ensure more appropriate future development and appropriate rebuild plans for the city. Learning from past mistakes and being more aware of hazards and the risk of hazards is an important step in building future resilience in Christchurch to not only seismic hazards but other coastal and river hazards. The lessons that have been learnt in Christchurch will hopefully be taken on board by other cities in New Zealand and worldwide, in order for them to try and avoid the same situation that Christchurch has had to endure.

5.7 Summary

The progress of recovery and the lessons learnt following the Canterbury earthquake sequence have been addressed in this chapter. The progress of recovery is discussed in order to observe whether or not the recovery progress influenced the ability of coastal and river environments to recover in a timely manner. The lessons following the earthquake have been discussed in order to establish what changes have been made, that may influence the resilience of Christchurch city to future hazards. Field work for this section, like the chapter before, included the interviews with experts from key stakeholder companies involved to a certain extent with the Christchurch rebuild. The data from interviews revealed several themes that relate back to the recovery of the city and the lessons learnt following the earthquake. These themes included ‘damages and costs’, ‘recovery and zoning’, ‘extent and scale’, ‘legislation changes’ and ‘awareness and lessons’.

The themes concerning damages, costs, recovery and zoning address the first question set out in this chapter which was ‘what recovery progress can be observed in Christchurch and how does this progress influence the city’s resilience to hazards’. The extensive damage and the enormous cost of the rebuild contribute immensely to how long the recovery of the city will take. The damage to essential lifelines and buildings was discussed in order to portray the extent of damage and create an understanding as to why the repair work will be done over such a long time frame (5 years, at this stage). The section showed that there was extensive damage in eastern suburbs and the CBD with coastal, river and cliff side suburbs the most severely impacted. This highlights that repair work will be most significant in the east, and particularly around coasts, rivers and coastal cliffs.

The ‘recovery and zoning’ themes also relates back to the first question as it provides information on what progress has been made since the earthquakes. This includes information on demolitions with the CBD and the gradual reduction of the CBD red zone cordon and the zoning of land into green and red zones and further categorising the green zones into technical categories. Most of the land zoned red has been around the Avon and Kaiapoi rivers, the Avon Heathcote Estuary, Brooklands Lagoon and the coastal cliffs around Redcliffs and Sumner. The areas around the Avon Heathcote estuary were one of the last places to know there land zone decisions which hampered the recovery of the residents that live there. The section highlights that progress following the earthquakes has centred mainly on the CBD and not on the suburbs where people are most affected. The demolitions and recovery within the city has been a priority and it would seem that recovery efforts in hindsight should have been more focussed on the suburbs and getting people back into undamaged homes.

The next three themes relate back to the second question ‘what lessons can be learned from the Canterbury earthquake sequence that is important for other coastal cities in New Zealand and worldwide?’ The unexpected scale and extent of the hazards associated with the Canterbury earthquakes was one theme that highlighted a lesson that sometimes a city can prepare for the worst case scenario, but often an event can exceed this expectation. It was predicted that Christchurch had potential liquefaction, lateral spreading and land slide risk in concurrence with an earthquake, but the scale of these hazards went beyond those predictions which forms a lessons concerning a city’s preparedness for hazards. The lesson being that it might be more valuable to try and plan for hazard events beyond the worst case scenario, so that a city can be better prepared to deal with the effects of a hazard event.

Changes to legislation following the earthquakes also serves as a way in which lessons are being made. Underpinning the flaws and failings of legislation that concerns managing the risk of earthquake hazards is an essential component of minimising risks for future hazard events. Without addressing governing legislation and making changes, lessons following the earthquake event would not be implemented and may in turn, not contribute to building greater resilience for the city. Following the Canterbury earthquakes there have been changes to the Resource Management Act, The Building Act and the experts also highlighted that it could be beneficial to consider making changes to The Ministry for the Environment guidance manual: Coastal hazards and Climate Change (2008) and The New Zealand Coastal Policy Statement (2010).

The last theme discussed is the ‘awareness and lessons’ theme which highlights that there is now an awareness of the development mistakes that occurred in Christchurch. There is an awareness that some areas of Christchurch that were developed never should have been and this contributed to a number a significantly damaged areas around coastal and river environments. In order for Christchurch to do better in the future, now that the known risks are understood in more detail, there needs to be positive actions taken to reduce these risks. These actions can be observed with the changes made to the RMA which gives greater consideration to natural hazards as well as changes to other legislative documents that govern building design standards which ensure an increase in buildings resilient to earthquakes. A lesson that was also addressed concerned the lack of awareness that the public had about the risk of earthquake induced hazards such as liquefaction, greater public awareness is beneficial for building resilience because what the public cares about is subsequently what the government cares about and takes action on. The Canterbury earthquakes will hopefully serve as a lesson for other cities in New Zealand and help build awareness of the potential risks of an earthquake and earthquake induced hazards in their region, particularly if their region is in coastal or river environments or in regions with steep terrain. It would seem imperative for other cities to look at the earthquake events in Christchurch and see where they can make improvements to their own management of hazard risk.

6 CHAPTER SIX: INTEGRATED DISCUSSION AND CONCEPTULIASATION

6.1 Introduction

This chapter presents an integrated discussion and conceptualisation of the Canterbury earthquake sequence. The discussion primarily draws from the concepts that were first reviewed in Chapter One as well as addressing the research questions presented in Chapter Two: *Are there specific natural features of past and present coastal and river environments that make them more vulnerable to earthquake induced hazards?, What features of the natural environment and the built environment were affected by earthquake induced hazards?, Has the Christchurch earthquake sequence influenced coastal and river environmental processes and future hazards? What recovery patterns can be observed in Christchurch and how do these patterns influence the city's resilience to hazards? What lessons can be learned from the Canterbury earthquake sequence that is important for other coastal cities in New Zealand and worldwide?* The chapter will conceptualise the concepts of natural disasters, vulnerability resilience and coastal management for the Canterbury earthquake sequence and will include the identification of key issues and lessons based on findings from this research.

This integrated discussion will explore key issues and lessons that can be derived from the Canterbury earthquake sequence, with regard to the concepts and research questions described above. This is done in order to both explore how the Canterbury earthquake sequence fits into the international context of natural hazards and disaster research and whether or not these international concepts can be applied appropriately for local scale hazard events, using the Canterbury earthquakes as an example. The first section of this chapter will address the Canterbury earthquakes as a natural disaster and explore what aspects of the earthquake determined its status as a 'disaster'. This section will also explore issues with terming the Christchurch earthquake event as a 'natural' disaster and will explore what factors contributed to the main impacts observed as a result of the earthquakes.

The next section will discuss the vulnerability of the Canterbury region to seismic induced hazards. As discussed previously, vulnerability has been a leading term in natural hazard literature and has led to a wave of research advocating social vulnerability as the leading cause of natural disasters. This section will explore what factors contributed to the vulnerability of the Christchurch region to significant earthquake induced hazards and attempt to establish whether earthquake impacts can be attributed to a combination of human vulnerabilities and natural vulnerabilities. This section will not discuss social vulnerability for the Christchurch region, as this has not been an objective of this research. However, it will explain the interaction that human systems have with natural environments, which can increase vulnerability and risk in the region. The city of Christchurch is embedded within two natural environments, the first being a coastal environment and the second being a river environment and it is the combination of these two environments that appeared to have contributed to the natural vulnerability of the city to earthquake hazards including liquefaction, lateral spreading and rock falls.

The next section discusses the concept of resilience and explores the past resilience that Christchurch had against earthquake hazards. This includes focussing on building standards and emergency procedures that were in place to ensure impacts of an earthquake would be minimal at best. This section will then discuss the future resilience of Christchurch following the earthquake recovery and determine whether or not actions taken as a result of the earthquakes will increase resilience within the city to earthquake induced hazards. The second to last section discusses coastal and river environmental management and how these dynamic environments should be managed in terms of earthquake hazards. Coastal and river environments have their own set of characteristics which make them more susceptible to damages as a result of earthquakes and other natural hazards and these characteristics need to be recognised by managing bodies so that appropriate decisions can be made with regard to future development.

Analyses presented in this chapter draw on key issues and lessons derived from the information provided by the interviews with experts and the information provided by international literature. The lessons drawn from the previous two chapters are analysed further within the wider context of natural hazard management and the dynamic links between environmental processes and development on coastal and river plains are addressed. In addressing these links, attention is given to understanding the interplay between economic interests and sustainable development, which is at times a contentious issue, particularly in coastal and river areas that are generally perceived as ‘prime blue edge’ real estate.

The last part of this chapter discusses the challenges in managing potential seismic events that are currently faced by regional authorities in other coastal cities in New Zealand. Large cities such as Wellington that have a high risk of seismic activity will now be looking at the Christchurch earthquake as an example of what their city could expect if the same magnitude earthquake was to occur. Attempts should now be made to implement ways that these coastal and river cities can identify and reduce their risk and thus minimise potential effects.

6.2 Canterbury's Natural Disaster

There has been debate in previous literature about the use of the word 'natural' when discussing a disaster or hazard event. As previously discussed in Chapter One, a natural hazard is an element of the physical environment that upon interaction with human systems is harmful to people, with the harm being caused by forces which are extraneous to the human system (Burton and Kates, 1964). A natural hazard becomes a natural disaster when a hazard event overwhelms the coping capacity of the human system and causes severe consequences for both people and the environment and the more people that reside in the area at the time, the larger the extent of the disaster through loss of life and property (Alcantara-Ayala, 2002). Extreme natural events do not always lead to natural hazards or disasters when they occur with no human interaction. For example, in an empty desert a natural event such as an earthquake, may be strong but should not lead to a disaster as there are no people or property affected (Pate *et al.* 1994). As such, disasters mark the interface between extreme natural phenomenon and vulnerable human populations (O'Keefe *et al.* 1976). Exactly what harms which people and property during a hazard event is the key question when discussing natural hazards and disasters. For example, in an earthquake event, people should rarely be harmed, but most casualties from an earthquake are due to collapsed buildings, which reflects poor building design and does not reflect harm that can be seen as either 'natural' or 'environmental' (Hewitt, 2007).

People are subject to the negative effects of natural forces, so it would seem appropriate that people would try to avoid inhabiting places where natural events are likely to occur. However, people are not always aware of the threat posed by rare natural events or they feel safe because of the long quiet time between event occurrences and as a result settlements are established in regions that are at risk of extreme natural hazards (Pate *et al.* 1994). Earthquakes are one such event that can stay quiet for thousands of years but their potential occurrence is often well identified. The Canterbury region in New Zealand is one such region that has well documented active earth deformation, related directly to its location to the wider Australia-Pacific plate boundary zone (Pettinga *et al.* 2001). Multiple historic earthquakes have occurred throughout the Canterbury region, indicating that the risk of an earthquake to be felt within the Christchurch city area was possible. Using the distribution of active faults and historic records of earthquakes a study by Stirling *et al.* (2001) estimated the strongest level of ground shaking (PGA=0.7g or more) had a return period of 475 years and could be expected in the north to north west of the Canterbury region (Stirling *et al.* 2001).

The Canterbury earthquake sequence which began with the September 4th 2010 earthquake, can be considered as a natural event but was not considered as a natural disaster, as there was no loss of life, buildings had not collapsed and people's homes were not left completely uninhabitable. However, there was significant damage done to buildings within the satellite suburbs of Kaiapoi, mainly due to liquefaction and lateral spreading and there was also damage to buildings and infrastructure particularly in the CBD, southwest and eastern Christchurch, making this a natural hazard event.

The February 22nd earthquake in 2011 however, can be considered as a natural disaster due to the significant loss of life and extensive number of injuries and damage to buildings and infrastructure which overwhelmed the city and country's ability to cope. It was previously recognised that an earthquake could occur within Canterbury and be strongly felt in Christchurch. Conversely there was less awareness about the risk of an earthquake occurring within such close proximity to the city itself. This was because there was no historic indication or evidence of earthquakes or active faults beneath or immediately surrounding the city (Pettinga *et al*. 2001). This could imply that the people residing in Christchurch may have felt safe from an earthquake event occurring close to Christchurch because there had not been a significant earthquake event in the area in recent history, however people were most likely aware of potentially experiencing the effects of an earthquake from the wider Canterbury region, particularly as a result of a rupture on the Alpine fault. In saying this, it still seemed that the effects associated with the earthquakes including liquefaction, lateral spreading and rock falls did come as a surprise, especially to the public, who were primarily not prepared for the effects of these hazards. The effects of liquefaction, lateral spreading and rock falls were the main hazards generated as a result of the September 2010 and February 2011 earthquakes and it was these hazards that caused a majority of damage to buildings and infrastructure within and surrounding Christchurch (Cubrinovski *et al.* 2011).

As discussed in Chapter Three, the main reason for loss of life and injuries as a result of the February earthquake was due to the complete collapse of buildings and falling debris from old un-reinforced masonry buildings and two reinforced concrete (RC) buildings (Ingham *et al.* 2011; Weng Yeun and Pampanin, 2011). Damage to masonry buildings including churches was widespread throughout the city and severe damage occurred to many buildings that had been classified as earthquake prone prior to the Canterbury earthquakes (Kaiser *et al.* 2012). The Christchurch earthquake represented one of the most severe tests of both modern and older RC buildings in a developed nation that has a strong seismic engineering background. Around 16.2% of 833 RC buildings within the CBD were severely damaged during the February earthquake and 135 of the 182 fatalities were due to the complete collapse two RC buildings (Kam and Pampanin, 2011).

The extensive loss of life and injuries in culmination with damage to infrastructure deemed the Christchurch earthquake event to be a disaster. It was the most deadly earthquake in New Zealand since the 1931 Hawkes Bay earthquake and the most expensive disaster in New Zealand's history (Cubrinovski *et al.* 2011 and Kaiser *et al.* 2012). The factors that contributed to the deaths and injuries during this earthquake was certainly not from natural causes, as noted above it was the collapse of buildings that caused the majority of deaths and injuries and as such the collapse of buildings is not a 'natural' occurrence but a 'human' one.

International literature would consider the February 2011 earthquake to be a natural disaster, due to the event exhibiting severe negative consequences for both people and the environment. The natural environment suffered negative effects associated with the earthquakes particularly in the rivers and beaches. Christchurch's rivers were affected following the effects of liquefaction (input of sand and silt) bank slumping, stream bed uplift and input of raw waste water. On the 15th of March 2011 an estimated 35 000 m^3 of wastewater was discharged per day into Avon river but fortunately by April 28th 2011 this amount of discharged dropped to 13,300 m^3 per day. In the Heathcote river, discharges were estimated to be about 13 000 m^3 per day and caused severe de-oxygenation. These discharges had effects on the aquatic life within the rivers as well as impacted recreational use of the rivers. Provided that the discharge in the Avon River stayed under 10 000 m^3 per day and 5 000 m^3 per day in the Heathcote River, effects on fish and invertebrate communities were unlikely (McMurtrie, 2011).

The Avon-Heathcote Estuary also suffered adverse effects due to changes in bed height, bathymetry, the input of sediment from liquefaction and the input raw wastewater discharge. This changed the habitat conditions of the estuary and consequently had effects on marine biodiversity (Zeldis *et al.* 2011). There was also discharge of wastewater into the beaches of Christchurch which impacted water quality and hindered the recreational use of beaches surrounding Christchurch for up to 12 months.

A few decades ago, people assumed that disaster such as earthquakes were themselves natural disasters and it was accepted that their impacts could be reduced through preparedness, mitigation and emergency action (Cannon, 1994). Recently, however, there has been greater acceptance of the idea that many natural disasters are inherently caused by human actions and the human environments. The Canterbury earthquake sequence supports this idea, in this case, as loss of life and injuries were a result of collapsing manmade structures and not from the earthquake itself. However, the majority of infrastructure damage and building damage in the eastern suburbs did not come down to the poor design of buildings, but was generally due to the existence of past and present natural coastal and river environments that the eastern suburbs are imbedded within. It was the natural features of coasts and rivers that induced the occurrence of liquefaction, lateral spreading and rock falls that caused a majority of damage in eastern Christchurch. Further discussions on this point are provided in the next section. As such, the Canterbury earthquake sequence could be considered a case for putting the 'naturalness' back into natural disasters as opposed to the present view in literature that considers taking the 'naturalness' out of natural disasters and places the blame for disasters on people alone and not on past or present environmental conditions.

This section concludes by clarifying that hazard events (earthquakes) are natural, but that disasters in general are not natural, but are induced by a combination of natural and social vulnerabilities. Over all, disasters should not be seen as the inevitable outcome of an extreme natural event's impacts but in terms of the vulnerability and resilience of the impacted population. The main point to look at when trying to establish what makes it possible for a hazard to become a disaster is to establish the vulnerability and resilience of a population to a given hazard - this should include a consideration of both natural vulnerability as well as social vulnerability. The next section of this chapter will aim to further discuss the vulnerability of Christchurch's coastal and river environments to earthquake hazards and aim to compare the vulnerabilities observed in this study of the Christchurch earthquakes to those emphasised in literature today.

6.3 Coastal and River Vulnerability within the Canterbury Region

Vulnerability, as discussed in Chapter one, is a fundamental concept in hazard research and is now essential towards understanding why hazard events become disaster events (Cutter, 1996). As noted in the above section, not all hazard events become a disaster. A disaster is recognised now as the undesirable outcome of the interaction of two main factors 1) a hazard impacting on a community and 2) the community having a degree of vulnerability to the characteristics of the hazard (Stenchion, 1997). Vulnerability can stem from a wide range of different characteristics and is not only based on social vulnerabilities but also on environmental vulnerabilities. Disasters occur when the interaction of hazard and vulnerability is such that the community suffers significantly as a result, in the form of loss of life, injury and damage to property and essential lifelines (Stenchion, 1997).

Vulnerability is defined as the potential for loss and is now central to the development of hazard mitigation strategies (Cutter, 1996). Assessments of vulnerability within a community are used to determine the potential damage and loss of life as a result of an extreme natural hazard. In the early years of disaster research, social vulnerability to hazards was rarely discussed and mitigation and hazard reduction strategies usually took the form of structural and engineered approaches. Presently, social vulnerability forms an integral component for assessing disaster reduction for a community. Worldwide, it is now recognised and understood that poverty, over-population, un-sustainable development and environmental degradation are leading factors in increasing social vulnerability.

As part of this study, one of the aims was to establish the vulnerability of coastlines and rivers to earthquake hazards. When observing the patterns of effects of earthquake induced hazards including liquefaction, lateral spreading and rock falls, it became apparent that the spatial distribution of effects could not be deduced down to socially imbedded factors of vulnerability alone. It appeared that the distribution of damage in Christchurch as a result of earthquake hazards was predominantly around rivers, estuaries, lagoons and coastal cliffs. It appeared that there were no areas of Christchurch that were more damaged than others, for reasons rooted only in social structures alone. As discussed in Chapter four, there are underlying natural features of coastal and river environments that have made them more vulnerable to earthquake induced hazards.

Earthquake damage occurred to both new and old infrastructure and damage could not be classified as only impacting old or poorly built structures but also impacted structures of new designs, which were thought to be able to withstand a significant earthquake (Buchanan *et al.* 2011). When looking at the effects of the earthquakes on buildings and structures, it becomes apparent that damage in Christchurch was not always a result of poor design standards but was a result of where the buildings were, in this case, the entire eastern fringe of the city was built within a predominantly coastal and river environment, which made the building vulnerable to the effects of liquefaction and lateral spreading. The role of coasts and rivers appears to play an integral role in the reason for why damage to entire new subdivisions, with up to date building designs was so extensive (Kaiser *et al.* 2012). This leads to an understanding that the damage to infrastructure is not only due to social vulnerabilities as there appeared to be no significantly disproportionate effects to building based on social differences, expensive housing areas were just as damaged as cheaper housing regions, however social vulnerability was not a main objective of this study and should not be discounted all together based on these findings.

Coasts and rivers were the main two themes discussed during the interviews and experts recognised that a majority of earthquake impacts were located around rivers and in the eastern suburbs, which lie on top of past marine and coastal deposits. Liquefaction, liquefaction induced lateral spreading, rock falls and the slumping of the land were significant aspects of the Canterbury earthquake sequence (Cubrinovski *et al.* 2012). These hazards were also main themes discussed with the experts with regard to these earthquakes and the experts recognised that these hazards were the main cause of damage to both residential and commercial buildings and infrastructure. The experts also recognised that liquefaction and lateral spreading, triggered during the larger earthquakes, was due to naturally occurring past and present coastal and river features, that Christchurch city is embedded within.

The reason why extensive liquefaction occurred in the eastern suburbs was because the underlying sediment comprises of unconsolidated sand and silt and the ground water level is high (less than 1 m below the surface). The experts agreed that these two factors together with ground shaking is the reason for why extensive liquefaction occurred. Experts also agreed that the reason for why these particular sediments are found in the eastern suburbs is due to the past coastal environment of the city together with past and present river channels that have laid down sediments for thousands of years. Although the phenomenon of liquefaction appeared to be a relatively un-heard of event, this hazard has occurred frequently during a number of other international earthquakes, where non-coincidentally, the liquefaction events occurred in coastal areas.

The study by Bird and Bommer (2004) conducted a study of 50 international earthquakes and found that liquefaction was reported in 62% of them. The 1995 Kobe earthquake is one example, where the gravelly Masado material at Kobe Port liquefied and caused extensive damage to the port. Liquefaction has frequently occurred in reclaimed soils, in coastal areas and poorly compacted man made fill areas worldwide, examples of this include Kobe Port, Japan; Marina district of San Francisco and Manzanillo, Mexico. Liquefaction also occurred in alluvial and deltaic deposits including old and existing river bed, for example in Dagupan, Luzon; Ceyhan, Turkey; and the Rann of Kachchh in Gujarat, India (Bird and Bommer, 2004). These many examples of coastal and river areas that have experienced liquefaction and liquefaction induced lateral spreading shows that what has happened in Christchurch was in fact, not a rare phenomenon. This shows that there needs to be greater attention paid to the existence of natural vulnerabilities within coastal and river communities to the hazards brought about by earthquakes.

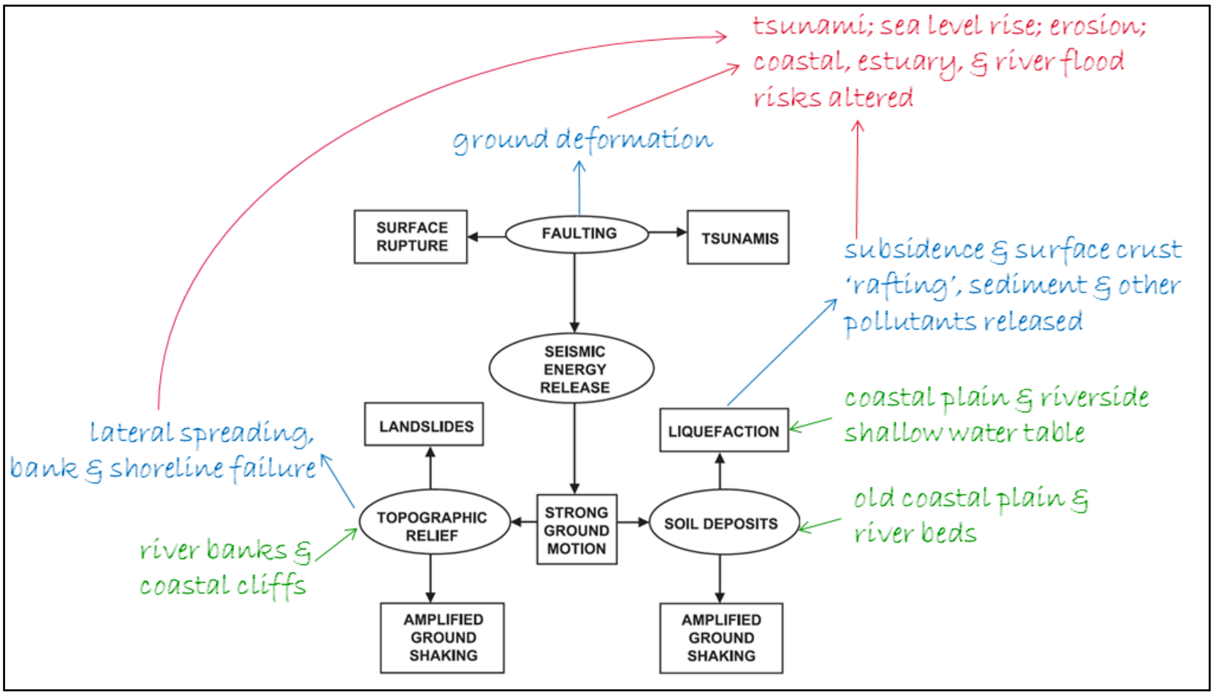


Figure 6.1: The black parts of this figure are from Bird and Bommer (2004) indicating what hazards can be associated with an earthquake. The coloured parts indicate aspects of these hazards that can be related back to coastal and river environments (Source: Hart *et al.* 2012).

To conclude, present natural hazard literature focuses to a greater extent on social vulnerabilities of communities to disasters and hazard events and somewhat less on natural vulnerabilities. The literature of the past had a greater focus on the natural environment when discussing hazards and disasters and put a majority of the blame for disasters on nature. In other words damage and destruction was regarded as a result of magnitude, frequency and the speed of onset of a hazard and not on the diverse actions of people that play a role in disasters (McEntire, 2004). What is needed now and what many papers conducting hazard analysis today are attempting to do is to identify hazard risk by combining the vulnerabilities of both the natural environment and the human environment, in order to gain a greater understanding of vulnerability for a community to a certain hazard.

6.4 Christchurch's Resilience to Earthquake Hazards

The most damaging natural disasters occur when natural hazards such as earthquakes, tsunami and floods interact with people of the world's poorest nations. These hazards disproportionately impact people's lives where a majority of the population lack the financial capacity to be resilient to the hazards that they face (Kahn, 2005). However, the Canterbury earthquake sequence tested one of the worlds' most seismically resilient nations. These earthquakes challenged some of the best enforced, high quality building codes and shocked a city that was thought to be relatively resilient to the effects of earthquakes (Kaiser *et al. 2012*).

As discussed in chapter One, resilience and vulnerability are central concepts in understanding disasters. Vulnerability is the pre-event characteristics of a social or environmental system that creates the potential for harm, while resilience is ability of a social or environmental system to respond to and recover from disasters (Adger *et al.* 2005). This includes pre-event conditions that allow the system to absorb impacts and cope with the event and post-event adaptive processes allows the system to respond, learn and change in response to the disaster event (Cutter *et al.* 2008). Three elements are crucial for building resilience; these are 1) communication, which is essential for hazard awareness and action 2) positive cultural and political characteristics, which influence the ability of the community to cope and 3) adaptive capacities of the community, including available resources, finances and skills (Vogel *et al.* 2007).

It is therefore apparent that in order to mitigate the effects of disasters, the scientific community in collaboration with local governments need to explore both physical and social factors that influence resilience (Hill *et al.* 2012). This section will discuss the resilience of Christchurch City to earthquake hazards, as a result of the Canterbury earthquake sequence. The discussion will draw information from the expert interviews and will focus on the themes of damage, awareness and recovery. The focus within a majority of international literature in terms of resilience has been centred on impoverished nations. As such, this section will highlight international examples of other natural disasters impacting wealthy, prepared, and politically stable and hazard aware nations, like Christchurch and this should assist the scientific community to better understand the concept of resilience.

There is a severe contrast in the economic impact of earthquakes. While the cost of an earthquake event in a developed country such as Japan, California or New Zealand is large, the loss of GDP is small compared to that of countries such as Haiti. The Tohuku, Japan earthquake is likely to be the most costly earthquake disaster to date, with an estimated US$200 billion repair bill, yet this cost is only 3-4% of Japan's GDP and the repair bill following the Canterbury earthquakes is estimated to be US$15 Billion which accounts for 10% of New Zealand's GDP (Parker and Steenkamp, 2012). While in Haiti the repair bill of US$8 Billion will cost the country their entire year's worth of GDP. This shows that developed countries like New Zealand and Japan are financially resilient to disasters, as they have the capacity to absorb the cost of a damaging hazard event and recover from the event in a timely manner.

The extent of damage was a common theme discussed as a result of the interviews in this research. Damage to buildings and infrastructure was severe, particularly in the CBD and eastern suburbs. The expert's opinions on the cause of damage was centred on the fact that ground shaking as a result of the February earthquake was intense enough to cause the collapse of buildings within the CBD and cause significant liquefaction and lateral spreading which caused widespread damage to homes and infrastructure. The day after the February event 60% of households did not have electricity, 50% did not have water and 40-50% did not have waste water facilities, however in 1 month, 99% of households had electricity, 95% had water and 80% had wastewater facilities restored (Stevenson *et al.* 2011).

The relative speed of restoring essential lifelines to households is another piece of evidence for greater resilience within Christchurch city. Sonia Giovinazzi explained that some lifeline facilities performed better than others: the gas system was new, so it performed well under the effects of the earthquake, whereas the water system was old, so it was more prone to damage. The ongoing repair of lifelines following the earthquakes are aiming for greater resilience in lifelines to future earthquakes, as the experts explained, a large amount of work is going into understanding how to make sure lifelines function sufficiently during earthquakes with regard to the soils that they are being built into. This is important because lifelines in the western part of Christchurch were not as badly damaged as those in the east and this was put down to the type of soils the lifelines are built within. The fine sand and silts and the high water tables of the eastern suburbs made the soils more vulnerable to the process of liquefaction and thus made the lifelines more vulnerable to damage during an earthquake. The Canterbury earthquake sequence highlighted the established seismic resilience of New Zealand, despite the surprise location of the faults. Resilience was highlighted in building performance as buildings that were designed to withstand shaking from larger earthquakes further away, fared well and while a large number of buildings and homes and have been or are still destined to be demolished, they still stood up long enough for people to evacuate them (Buchanan *et al.* 2011).

Another theme resulting from the interviews was that of awareness. Awareness of hazard risk plays an integral role in the resilience of both people and their communities. Awareness of hazard risk means that people are more prepared and know what to expect and how to act in face of a hazard event. In terms of resilience, the New Zealand public is supposedly a relatively well prepared earthquake community - in the world, the government provides comprehensive earthquake preparedness for schools and Civil Defence provides advertisements on what people should be prepared for and what to do in the event of an earthquake.

Graham Harrington pointed out that an earthquake located very close to Christchurch was not major risk in Christchurch. This is because there was no evidence of active or historical faults located close to the city. Because evidence of these faults had been hidden by deep alluvial sediments and the only conceivable earthquake threat to Christchurch was that from the Alpine Fault. However, the Christchurch Engineering Lifelines Project published "Risk and Realities" in 1997 which stated that the risk of an earthquake to Christchurch would be from either the Alpine fault, the Canterbury foothills or conceivably close to Christchurch or under the Canterbury plains. They concluded that all three scenarios could produce shaking intensities of up to MM 8.0, yet longer duration shaking from a larger earthquake such as the

Alpine fault would produce more damage and more extensive liquefaction (New Zealand Centre for Advanced Engineering, 1997).

In Christchurch the risk of hazards such as liquefaction and lateral spreading were identified and it is now apparent that many subdivisions were built into areas of known high risk and yet, the people living there were not aware of this risk. It appears that the public were aware that of the risk of feeling an earthquake within Christchurch but were not aware of the risk of liquefaction or lateral spreading. The experts agreed that the risk of liquefaction was known about among the scientific community and that there were areas of Christchurch that should not have been built on at all given the risk. However, the importance of economic growth appears to be the reason for why developments in these areas went ahead regardless of this risk.

One aspect of resilience is the ability of a community to learn from past mistakes and to ensure that after a disaster they endeavour to build back better (Lynos, 2008). It appears that these lessons are being learnt through the process of re-classifying land into technical categories that defines the type of foundations and building design needed for that type of land. As discussed in Chapter Five, areas of land around the Avon River, Kaiapoi River, Brooklands Lagoon and the Avon Heathcote Estuary, which were badly damaged due to severe lateral spreading have now been red zoned, this means that development will not occur again in these areas. This indicates that a lesson has been learnt about developing close to river banks and estuaries, as Bob Kirk stated "*there can be economic development without putting areas at risk, it is about developing wisely*" and it does appear that wiser development choices have been made around rivers and estuaries in Christchurch.

There have also been amendments made to the Resource Management ACT 1991, which ensures that new developments would now have to have greater regard for natural hazards than they had before. These changes were made in light of the Canterbury earthquakes, when it became apparent that some developments in Christchurch, which were badly damaged, had been consented through the RMA, when they never should have been. Both these actions post the earthquakes are indicators that a greater resilience is being built into Christchurch and wider New Zealand in terms of adapting to earthquakes and their associated hazards.

Overall, resilience is about encouraging sustainable development and ensuring that reconstruction does not reproduce previous vulnerabilities for the future (Lynos, 2008). Christchurch now faces a difficult road to recovery after their 'everyday' hazard took them by surprise. It was thought that New Zealand was relatively resilient to earthquakes through its strict building codes, but the earthquakes in Christchurch have highlighted major flaws within the country's building code and insurance system. Other countries in earthquake prone regions such as Japan, design buildings that will not experience damage during an earthquake where as in New Zealand the Earthquake Insurance system (EQC) relies on replacing and repairing damaged buildings after an earthquake. Unfortunately the Canterbury earthquakes nearly bankrupted EQC, with claims made to the EQC net of reinsurance cover exceeding NZD $7 billion, consequently demonstrating that this system of insured replacements is a failure (Parker and Steencamp, 2012). The road to recovery in Christchurch will not be easy and there will be mistakes made along the way, which may hinder the resilience of the city and wider New Zealand. If mistakes regarding the management of natural hazards are not recognised and managed appropriately this could lead to reproduced vulnerabilities and cause a repeat of the disastrous effects seen in Christchurch and in other coastal and river cities worldwide.

6.5 Management of Earthquake Hazards in Coastal and River Cities

One of the greatest threats to the sustainable management of coastal zones is the exponential growth of coastal populations (Duxbury and Dickinson, 2007). An increase in coastal populations puts increased pressure on coastal resources through increases in coastal development. The real estate premium of coastal land further creates issues with the way in which competing uses for coastal land is managed. The same increasing trend can be seen in populations concentrated around rivers. Rivers and river mouths are attracting larger population because of the essential resources that they provide, such as freshwater and food.

Coping with natural hazards is a critical element of how resources are used and how human settlement has evolved. With the number of people residing in coastal and river environments increasing, the exposure of people to natural hazards such as flooding, tsunami, storms and as recently discussed, earthquakes, will also increase. As such, a greater number of adaptive responses are needed in coastal and river zones in order to cope with these hazards as well as similar hazards arising as a result of global climate change (Adger *et al.* 2005).

This section will discuss issues within coastal and river management, with regard to earthquake hazards. These issues arise from events highlighted by the Canterbury earthquakes which, caused significant damage around coastal and river areas of Christchurch city. Sustainable management of coastal and river zones has been always been one of the most important objectives for governing councils within New Zealand. As discussed in Chapter One, this is due to the country's inert connection with coasts and rivers and the acknowledgment that these environments provide essential resources that need to be safeguarded for the future. However, an increase in development in coastal and river zones has occurred in New Zealand, which has placed a large proportion of the population along coastlines and river flood plains. Consequently a majority of the New Zealand population is at risk to many natural coastal and river hazards.

The risk of floods and storms impacting New Zealand is relatively high because of the countries maritime location. Coastal and river hazards are well documented within New Zealand as much of the country has experienced storms, which cause flooding of low lying coastal areas and increased rainfall causes flooding of river plains. The risk of an earthquake impacting New Zealand is also relatively high because of the location of the Australian and Pacific plate colliding in the middle of the country. New Zealand has some of the most detailed seismic hazard models in the world and the risk from earthquakes was thought to be relatively well understood (Pettinga *et al.* 2001). However, evidence from the Canterbury earthquakes reveals that there were proficient failures in the management of earthquake hazards and in particular the management of earthquake hazards around coasts and rivers.

The themes that will be discussed in this section, in order to address these management issues are centred on coastal and river damage, potential changes to coastal and river hazards, the rezoning of land and changes to legislation following the Canterbury earthquakes. As previously discussed a majority of the damage to Christchurch occurred around rivers and in particular the Avon River in Christchurch and the Kaiapoi River north of Christchurch. Damage around rivers was due to earthquake induced lateral spreading, which saw the banks of rivers collapse inwards. Most bridges in Christchurch are major roads which provide access to Christchurch's coastal areas and a majority of bridges were damaged around rivers which hampered evacuations and emergency response.

Along coastal areas many major roads were also damaged, in particular Main Road, which runs along the Avon Heathcote Estuary and out towards Sumner Beach, was badly damaged due to the collapse of the coastal cliffs. Many homes were damaged by rock falls and cliff collapses along the top of the cliffs and along the coastal zone beneath them. Taken as a whole, the coastal areas of Christchurch suffered from severe damage to roading infrastructure and essential lifelines which left areas isolated in places. Coastlines beneath cliffs were also badly damaged due to the collapse of coastal cliffs. Along rivers damage was severe due to liquefaction and lateral spreading which caused settlement of the land and induced damages to homes and infrastructure. The experts all acknowledged that the majority of damage to land and infrastructure occurred along river banks, the Avon Heathcote Estuary and along coastal cliffs.

As addressed in Chapter Five, it seems that previously, much of the risk of an earthquake and liquefaction was known and quantified in Christchurch, yet development still took place in areas of known high risk. The reason being, that the risk must have been simply discounted in favour of economic development. The experts recognise the fact that the risk of these hazards was identified yet development still occurred in places that it should not have and as a result the risk turned out to be greater than expected. This shows a mismanagement of coastal and river zones in terms of earthquake risk, because scientific experts were aware of the risk of liquefaction yet the people residing in these coastal and river areas appeared to have not. As a consequence, the government did not have an interest in making sure that coastal and river areas are developed and managed in a way that would decrease the risk of liquefaction and as a result the Canterbury earthquakes took effect. This is due to a fact, brought up by Marion Irwin that governments care more about what the public think more than what the experts know and in this case the public were not aware of the risk posed to their properties due to liquefaction, so no action was taken by governing bodies to do anything about decreasing this risk.

Another aspect about coastal and river management that comes into play in terms of earthquake effects is the changes that an earthquake event can have on other coastal and river hazards. The management of coastal and river hazards such as flooding, coastal erosion, storm surge, tsunamis and long term sea level rise are compromised when an earthquake changes the base level states that are used to monitor these hazards. As discussed in chapter four, the February earthquake caused a change to the level of the land in the eastern areas of Christchurch, the northern part of the city's east is now lower and the southern part of the east is now higher than before the february earthquake (Cubrinovski *et al*. 2011; Kaiser *et al.*2012).

The change in the level of the land caused a change to present coastal and river hazards and consequently all monitoring programs for these hazards now have to to be re-adjusted to the new base line conditions. For example the northern part of the Avon Heathcote Estuary has subsided by 0.2 to 0.5 m (Measures *et al.* 2011) resulting in an increased susceptibility for this area to flood during storms and extreme high tides. In terms of long term sea level rise, it would seem appropriate that adjustments need to be made to observe what increase in sea level could be expected now for parts of Christchurch that has undergone subsidence following the earthquakes.

As addressed in chapter Four, the Ministry for the Environment sets out that New Zealand has to prepare for a base sea level rise of 0.5 m by 2100 relative to the 1980-1999 average and that all planning assessments need to consider the consequences of a mean sea level rise of 0.8 m by 2100 relative to the 1980-1999 average (Ministry for the Environment, 2008). But, as the experts pointed out, how can these sea levels be addressed correctly when places such as northern Christchurch have already undergone subsidence and consequently sea level rise over a matter of seconds, as a result of the February earthquake. This highlights a flaw in the Ministry's guidance manual for preparing for sea level rise, as all areas of New Zealand's coastline are not at the same elevation, so how can they all prepare for the same amount of sea level rise. As Bob Kirk explained, there needs to be a regional or local amount of sea level rise relative to the elevation of the land that should be prepared for at any given place, not an arbitrary number set down by the IPCC for global eustatic sea level rise.

A second issue arising from discussions with the experts with regard to coastal management is that some of the re-zoning decisions around the Christchurch coastline did not have regard for sea level rise or changes to other coastal hazards. As discussed in the previous section, the red-zoning of land around rivers is a positive step towards building resilience to earthquake hazards and was an appropriate management decisions. However, out towards the coastline certain areas that were thought to fit the 'red zone criteria' were zoned green (land appropriate for re-building). Green zoning the outer part of the New Brighton spit and the northern coast line of Christchurch, which are vulnerable to the effects of sea level rise, is not a step forward in terms of resilience against coastal hazards exacerbated by sea level rise.

Building resilience encompasses the ability to adapt and change after a hazard event which enables a population to be more prepared for hazard events in the future. Objective 5 in The New Zealand Coastal Policy Statement 2010 states that coastal hazard risks, taking into account climate change, are managed by:

- locating new developments away from areas prone to such risks

- considering responses, including managed retreat, for existing development in this situation; and
- protecting or restoring natural defences to coastal hazards

Yet, green zoning the outer coast of New Brighton Spit and the northern Christchurch coastline, which has undergone subsidence, does not take into account this objective. The re-zoning of land was an opportunity for the government to retreat people from the Christchurch coastline and fulfil its obligation for preparing for sea level rise in this region. In contrast the Waimakariri district, north of Christchurch City has made more appropriate management decisions with regard to developed coasts and rivers. This district includes the town of Kaiapoi and the coastal settlements of Kairaki and Pines Beach and as discussed in Chapter Three these areas suffered severe damage as a result of the September earthquake. Consequently the council has red zoned areas of Kaiapoi located close to the Kaiapoi River and red zoned a majority of the land in the two coastal suburbs. The coastal suburb of Brooklands is within the Christchurch City district and fortunately has been red zoned due to the same reasons that Pines Beach and Kairaki were. The decision to red zone these areas was based on the severity of land damage and the issue that the new flood management plan released by the Christchurch City Council meant that building levels had to be 1 meter higher than they originally were. This meant that houses that weren't damaged would be lower than these criteria and would have to be rebuilt too, which in the end is un-economical for the whole area. Yet, in making the decision to red zone these areas, the councils have simultaneously fulfilled some of their obligation under objective 5 of the New Zealand Coastal Policy Statement, to retreat and relocate high risk coastal suburbs away from the coast. It is unfortunate that this retreat has not happened in other coastal regions of Christchurch and that the opportunity is now lost.

Current coastal management legislation in New Zealand (The New Zealand Coastal Policy Statement, 2010) advises councils to have regard for coastal hazards. However, these hazards do not include earthquakes and their associated hazards. As discussed in chapter one, earthquakes have not been typically perceived as a 'coastal' or 'river' hazard and yet the results from this research indicate that earthquakes are a significant threat to developed areas within coastal and river environments and can exacerbate other 'typical' coastal and river hazards. To conclude, coasts and rivers from the past and the present have their own specific characteristics that make them vulnerable to the impacts of earthquakes and in particular liquefaction, lateral spreading and rock falls. As well as coastal and river characteristics creating vulnerabilities to these hazards, the locality of suburbs along coastlines and rivers and a lack of inbuilt redundancy in lifelines and infrastructure, also makes them more vulnerable to isolation in the event of a disaster.

This leads to a lesson that natural environmental vulnerabilities need to be considered when building new developments in coastal and river dominated regions and that building designs need to recognise the wider environment that they are built upon as well designing the building to withstand severe earthquakes. Coastal and river regions need to be managed in a way that increases their resilience to natural hazards and this includes building increased redundancy in lifelines and infrastructure in coastal and river areas. This fact will be particularly true for the city of Wellington, which is known to be one of the most high risk earthquake areas in New Zealand. It is a city dominated by hilly terrain and a small coastal zone that provides the main access way to the CBD. An improved redundancy in lifelines will be important for the city of Wellington. A greater awareness of earthquake induced hazard risk now persists within Christchurch and the wider New Zealand society, which is a positive step towards building resilience to future earthquakes.

6.6 Summary

This chapter presented a discussion and conceptualisation of the Canterbury earthquake sequence. The discussion was centred on the conceptualising the key natural hazard concepts introduced in Chapter one and addressing these concepts within the Canterbury earthquakes case study. The first concept discussed was ‘natural hazards and disasters’, this section looked at the how the Canterbury earthquake sequence ‘fits’ into the international criteria for natural disasters and discussed what makes a natural hazard become a disaster, using the Canterbury earthquakes as an example. This section concluded that hazards such as earthquakes involve natural events, but disasters that occur as a result of a hazard are inherently not natural. Disasters occur as a result of a combination of social and environmental vulnerabilities and addressing these vulnerabilities is imperative to building disaster resilient communities.

The next two sections of this chapter discussed the concepts of vulnerability and resilience, which are two key concepts in natural hazards literature. Assessments of vulnerability within a community are used to determine the potential for damage and loss of life as a result of an extreme natural hazard. Presently, research into social vulnerability makes up a majority of hazard and disaster literature. These studies place the 'blame' for disasters primarily on social issues within a community and do not focus attention on the natural environment, which in a given hazard event plays an integral role in increasing vulnerability. This study aimed to highlight the natural vulnerability that exists within coastal and river environments to earthquakes and earthquake induced hazards. The reason why natural vulnerability was given priority in this study was because there did not appear to be areas that differed significantly in damage, between areas of eastern Christchurch with new and expensive housing and areas with older housing. The pattern of damage was predominantly around rivers, cliff faces, the estuary, lagoons and in the eastern suburbs as a whole, which was once a marine environment. Overall, the patterns of damage in Christchurch as a result of the earthquake can be attributed to the natural characteristics of coasts and rivers, past and present, which have natural features that makes them more susceptible to earthquake induced liquefaction, lateral spreading and rock falls.

Resilience is ability of a social or environmental system to respond to and recover from disasters. This section discussed the resilience of Christchurch following the earthquake events. New Zealand, as a country, was thought to be relatively resilient to the effects of earthquakes, as it has some of the best seismic hazard models in the world, very strict building codes and the risk of earthquakes was well understood. The risk of liquefaction was identified and well understood among the scientific community, yet it appeared that this risk was not well understood by the public and was disregarded when development occurred in areas with a known high risk of liquefaction. This lack of public awareness and disregard for the risk within new developments increased the vulnerability of the city within these high risk areas. Following the earthquake events, Christchurch needed to learn from, change and adapt in order to increase its resilience to future hazards and not only earthquake hazards.

This increase in resilience can be observed in the rebuild decisions that have been made in Christchurch. This includes the classifying of land into areas where re-building is acceptable or areas where the land is too badly damaged and the risk of future hazards are too high, or that is deemed un-economical for a rebuild. Overall, resilience is about encouraging sustainable re-development and ensuring that reconstruction after a disaster does not reproduce previous vulnerabilities for the future. Christchurch, for the most part appears to have made responsible land use decisions particularly around rivers, however, some areas of land around the coast, that have been deemed fit for reconstruction, are questionable.

The last section discussed coastal and river hazard management. This section highlighted that earthquake hazards are not usually perceived as a ‘typical’ coastal or river hazard, even though the impacts of an earthquake on coasts and rivers can be severe. This section focussed on the effects that earthquake hazards have on other coastal and river hazards, which is achieved primarily through altering the elevation of the land. This section highlights that after an earthquake event, the changes to other coastal hazards need to be consider when rebuilding a community and that the risk of earthquake hazards need to be considered more in the development and management of coastal and river environments. Given that New Zealand is a country highly prone to a range of natural hazards, with a population concentrated around coasts and rivers. It is imperative that professionals and communities take on board Canterbury’s lessons concerning earthquake risk complexities if we are to improve disaster resilience. Lessons concerning earthquake risk in coastal and river environments will be presented in the next chapter.

7 CHAPTER SEVEN: CONCLUSIONS

Coastal and river environments are physically and ecologically complex, dynamic environments (Arthurton, 1998). At the same time they are increasingly developed for human occupancy as they are perceived as desirable environments to live in (Kullernberg, 2001; Collins and Kearns, 2008). Communities that reside near or within coastal and riverside areas are vulnerable to the impacts of their naturally occurring physical processes, which pose a hazard to the built human environment. Because of increasing human development in these areas, robust knowledge and management of these environments is essential to enable communities to cope with and recover from the impacts of natural hazards.

The purpose of this research was to provide an understanding how past and present coastal and river features create natural vulnerabilities to earthquakes and earthquake induced hazards, using the Canterbury Earthquake Sequence as a case study. This project employed a multidisciplinary methodological framework to document, analyse and understand the vulnerability of coastal and river environments to seismic hazards, which have not been perceived as a 'typical' coastal or river hazard in previous literature. This information can be used to help observe vulnerabilities in other coastal and river cities both in New Zealand and worldwide to assist with new development and management strategies that could decrease the vulnerability of coastal and riverside environments towards the impacts of seismic hazards.

The objectives of this thesis were to:

1. document past and present coastal and river environments within Christchurch to explain increased natural vulnerability to seismic hazards,
2. document the effects that earthquakes and earthquake induced hazards have on coastal and riverside environments,
3. analyse the recovery patterns in coastal and riverside areas of Christchurch to determine future resilience,
4. derive lessons that can be learned from the experience in Christchurch to reduce vulnerability to seismic hazards in other coastal and river cities in the future, and
5. assess ways to reduce vulnerability and increase resilience in coastal and river communities in general.

A summary of the main findings, lessons, limitations of this study and suggested areas for future research are presented in the following sections.

7.1 Summary of Main Findings

7.1.1 Coastal and River vulnerability to Seismic Hazards in Christchurch

Leading the inquiry throughout the results and discussion chapters were a number of research questions that assisted in achieving the objectives of this study. The following sections will provide answers to these research questions which in turn act as a summary of the main findings.

Are there specific physical features of past and present coastal and river environments that make them more vulnerable to earthquake induced hazards?

As addressed in Chapter three and four, there are a number of physical features of coastal and river environments from the past and the present that have induced vulnerabilities to earthquake hazards. The Christchurch CBD and the eastern suburbs were once a marine environment, the coastline reached about 6 km inland of its present location around 6,000 years ago (Brown and Weeber, 1992). Over the following years the coastline prograded back out towards its present location, depositing fine sand and silts over the CBD and eastern areas. Throughout this time frame the Waimakariri River avulsed several times, laying down fans of river gravels over the Canterbury region, while smaller spring fed rivers including the Avon and the Heathcote Rivers also laid down fine sediments over the Christchurch region (Wilson, 1976).

Subsequently Christchurch City is built upon a combination of old coastal and river sediments, and among present river channels, wetlands and estuaries. Early maps indicate that pre-urban Christchurch consisted of small pockets of dry land with predominantly wet marsh land with many shallow swamps and ponds. The water table beneath eastern Christchurch is relatively high, less than 1 m below the surface, and this is due to the extensive ground water aquifers that are located beneath the city (White, 2009). The water table is highest in the east and decreases towards the west of the city (Jacka and Murahidy, 2011).

The types of sediments found beneath eastern Christchurch are unconsolidated fine sands, silts, peats and gravels and together with the high water tables makes the area tailor made for liquefaction and liquefaction induced lateral spreading to occur, when an earthquake of sufficient size shakes the ground (Obermeier, 1996). Liquefaction was widespread throughout eastern Christchurch and rivers including the Heathcote, Avon and Kaiapoi were particularly affected by lateral spreading. Rivers are particularly vulnerable to lateral spreading because the water table is close to the surface along river banks. The river banks are also unstable due to the water logged sediments and easily collapse when the process of lateral spreading occurs.

Parts of Christchurch are also built on the slopes of the Port Hills and the eastern parts of these hills consist of coastal cliffs that run along the fringes of the Avon Heathcote Estuary and Sumner Beach. These coastal cliffs are old volcanic rock and suffered significant land slips and rock falls during the February earthquake, indicating that they are also vulnerable to earthquakes through direct ground shaking (Cubrinovski *et al.* 2011).

Interviewed experts agreed that it was the presence of liquefiable soils that was the main contributing factor for inducing damages in Christchurch and that those soils were present because of either coastal or river processes. To conclude, there are a number of both past and present coastal and river features within Christchurch, which combined with a seismic event, can create increased vulnerabilities to earthquake induced hazards.

What were the effects of the Canterbury earthquake sequence on coastal and river environments and the built environment in Christchurch?

The natural and built environment of Christchurch suffered effects as a result of the Canterbury earthquake sequence, particularly around rivers and coastal areas. The rivers, the estuary and local beaches suffered water quality issues as a result of waste water being discharged to water ways when pipes were broken due to liquefaction and lateral spreading. The areas surrounding rivers and estuaries suffered significant lateral spreading. The collapse of river banks and the extensive cracking, tilting and subsidence that accompanied lateral spreading caused damage to homes, roads, bridges and lifelines. This consequently blocked transportation routes, interrupted electricity and water lines, and damaged structures built in their path including stop banks. Extensive liquefaction occurred throughout the eastern suburbs, which caused flooding in entire suburbs and damaged homes and infrastructure. Un-reinforced masonry (URM) buildings within the CBD and wider Christchurch were particularly susceptible to the shaking induced by the earthquakes and the collapse of two

Reinforced concrete (RC) buildings led to a majority of deaths and injuries suffered as a result of the February earthquake.

The experts agreed that a majority of the damage experienced within Canterbury as a result of the earthquakes was around rivers and coastal areas. To conclude, the Canterbury earthquake sequence had a significant effect on the natural and built environment of Christchurch, particularly around rivers and the coast. This was due to the susceptibility of river areas to lateral spreading and the susceptibility of the eastern suburbs and estuarine environments to liquefaction. There is also a lack of inbuilt redundancy in lifelines within coastal areas and this makes them more vulnerable to earthquake hazard in terms of evacuation and rescue efforts.

Has the Christchurch earthquake sequence influenced coastal and river environmental processes and future hazards?

Due to the Port Hills fault rupture, the elevation of the land in Christchurch has changed, with subsidence in the north of the city and uplift in the south. This elevation change, in turn, caused changes to existing coastal and river hazards that already posed a risk to the city. Natural hazards including flooding, tsunami and sea level rise were exacerbated in places where the ground has undergone significant subsidence. In particular, in the areas of Christchurch that have subsided, such as, the northern part of the Avon Heathcote Estuary, where there is now an increased level of flooding risk during storms and the lowered level of the land compared to that of the sea exacerbates issues associated with sea level rise. As Justin Cope said, *"the earthquakes have not created new hazards but have exacerbated existing ones"*. However one expert did note that the uplift of the southern part of the coastline could improve the resilience of this area to coastal hazards.

The experts had differing opinions on whether or not the earthquake sequence has exacerbated specifc hazards but they did agree that a level of change either positive or negative has occurred to these hazards. To conclude, the Canterbury earthquake sequence has had an influence on existing coastal and river hazards and assessing and monitoring these changes should be an important component of the recovery process of Christchurch. It is subsequently important to recognise the influence that seismic hazards can have on present coastal and river hazards.

7.1.2 Patterns and Progress of Recovery in Christchurch

What recovery patterns can be observed in Christchurch and how do these patterns influence the city's resilience to hazards?

The majority of recovery efforts in the first year following the February earthquake focussed on bringing down damaged buildings within the CBD and assessing land and building damage throughout the suburbs in Christchurch and the wider Canterbury region. Opening the CBD back up to the public and creating the new Cashel Street Container Mall was a priority in the first year of recovery. The opening of the Cashel Street Re-start mall within 12 months after the February quake was testimony to quick recovery within the CBD. However, in the two years following the February quake, buildings within the CBD are still being brought down and the centre of the CBD is still not completely open to the public. Furthermore, homes in the TC3 designated category are still undergoing land assessments on an individual site basis, to decide whether or not homes are appropriate for a rebuild.

With regard to designating land zone categories to Christchurch suburbs, it was the eastern suburbs around the rivers, coasts and hills that took the longest to find out whether they were in a red zone or a green zone. This wait delayed recovery for the communities in these areas. The establishment of land zone categories builds resilience to future earthquakes, as areas that have been red zoned are areas that have suffered significant damage during the earthquakes. These red zones are primarily around the Avon and Kaiapoi rivers, the Avon Heathcote Estuary, The Waimakariri River mouth and the Hill suburbs of Banks Peninsula. As such, patterns of recovery are building resilience to earthquake hazards around rivers and coastlines. However, as discussed in previous chapters, recovery patterns do show that resilience to other coastal hazards has not been considered in certain parts of the Christchurch coastline, particularly around the coastal side of Brighton Spit, which will, in the future come under threat by hazards exacerbated by sea level rise.

To conclude, the pattern of recovery following the February earthquake showed that coastal and river areas have taken the longest time to be able to start the process of recovery due to the time delay in deciding whether or not these areas should be green or red zoned. Recovery progress is taking into account building greater resilience to future earthquake hazards through the land zoning categories, but, resilience to other coastal hazards through land use decisions is somewhat deficient.

7.1.3 Lessons

This section encompasses the last question raised in Chapter Two: What lessons can be learned from the Canterbury earthquake sequence that is important for other coastal cities in New Zealand and worldwide?

1. Communities need to be aware that coasts and rivers are vulnerable to earthquake induced hazards, including direct ground shaking, liquefaction, liquefaction induced lateral spreading, flooding, land slumping and subsidence, rock falls and landslides.
2. Coasts and rivers are vulnerable to earthquakes through a lack of inbuilt redundancy in essential lifelines, particularly over bridges. Developed coastal and river areas with known seismic risk need to build greater redundancy in essential lifelines.
3. New developments in coastal and river areas that are located in known seismic hazard zones need to consider the effects of liquefaction and lateral spreading.
4. There needs to be greater awareness that earthquake events have the potential to exacerbate existing coastal and river hazards and that these hazards need to be considered before decisions on future land use are made during the recovery phase of an earthquake event.
5. Earthquakes need to be considered in coastal and river management plans due to the profound effects that this hazard has on these environments.

7.2 Limitations of this study and Suggested Areas for Future Research

The greatest limitations to this study lie in the availability and acquisition of data sources. This is particularly true in the case of the number of expert participants that were available to provide information for this research. Due to time constraints and availability, the number of experts interviewed for this study was relatively small. A larger sample group of experts would have supplied a larger variety of backgrounds and would have provided a broader spectrum of information from different areas of expertise. This would have aided in providing more holistic information and would have enhanced the interdisciplinary component of this study. The expertise from the sample of experts in this study is not as broad as what it could have been and areas for future research could address gaps in information by including a greater number of experts from fields such as biology, geology, and seismology.

The interviews in this study were the primary source of qualitative data, which has the drawback of incorporating data that is biased towards the expert's own experiences, knowledge and interests. To avoid this bias, future research could incorporate more quantitative data in forms of a questionnaire, from a larger sample of experts. This would create a data set from a set of questions with multiple answers that the expert could choose from. This creates an improved comparison of the experts' knowledge and derives transferable answers to the questions without doing complex qualitative data analysis. The integration of both qualitative and quantitative research methods can greatly expand the process of data collection and the depth of data analysis because quantitative research provides valuable background context while qualitative research provides a more vivid, dense and full description of the phenomena under study.

GIS derived data sources were to be the source of quantitative data in this study. However, the availability of data sources and GIS layers regarding the Canterbury earthquakes was limited due to the contentious issues surrounding the information. As such, GIS derived maps in this study had to be obtained from secondary sources and there is a limitation on being able to analyse secondarily sourced maps in GIS. Future research may have the option of obtaining these essential data sources, once issues surrounding their use have diminished.

In terms of vulnerability, only natural vulnerability was looked at in this study while aspects of social vulnerability, although recognised as a key component of a holistic understanding of hazards, were left outside the research scope. Due to the small time frame to conduct this research, it was not feasible to be able to include both natural and social vulnerability - and natural vulnerability both appeared to have greater gaps in present day literature and aligned well with the key research strengths of the author. As discussed previously, social vulnerability is an important component of natural hazard research and future research into the effects of earthquakes on coasts and rivers should aim to incorporate aspects of social vulnerability to create a fuller picture of the seismic hazards-coastal/fluvial linkages.

Finally, it is important to recognise that what has happened in Christchurch has the potential to happen in other coastal and river cities in New Zealand and around the world. This study only used the one case study to research the vulnerability of coasts and rivers to earthquake hazards. An enormous benefit would be gained in this area of research, if a study could look at other locations in the world, where the effects experienced in Christchurch has also occurred. This could assist in identifying global patterns of natural vulnerability that lay within coastal and river environments and recognise that what happened in Christchurch is not just a ‘one off’. Science and management, worldwide, could benefit greatly through a study of what made the effects of Canterbury earthquake sequence significant and recognise where else in the world, could this type of disaster event happen again.

REFERENCES

Adger.W.N, Hughes.T.P, Folke.C, Carpenter.S.R, Rockstrom.J, (2005), Social-ecological resilience to coastal disasters, *Science,* Vol. 309, Pp 1036-1039, DOI: 10.1126/science.1112122

Ambraseys.N and Sarma.S, (1969), Liquefaction of soils induced by earthquakes, Bulletin of the Seismological Society of America, Vol. 59, No. 2, Pp 651-664

Alcantara-Ayala.I, (2002), Geomorphology, natural hazards, vulnerability and prevention of natural disasters in developing countries, *Geomorphology*, Vol. 47, Pp 107-124

Arthurton.R.S, (1998), Marine-related physical natural hazards affecting coastal megacities of the Asia-Pacific region- awareness and mitigation, *Ocean and Coastal Management*, 40, 65-85

Ballinger. R.C, Potts.J.S, Bradly.N.J, Pettit.S.J, (2000), A comparison between coastal hazard planning in New Zealand and the eVol.ving approach in England and Wales, *Ocean and Coastal Management*, Vol. 43, Pp 905-925

Baird.A, Polermo.A, Pampanin.S, (2011), Facade damage and assessment of multi-storey buildings in the 2011 Christchurch earthquake, *Bulletin of the New Zealand Society for Earthquake Engineering*, Vol. 44, No. 4, Pp 368-376

Barth.M.C, Titus.J.G (eds), (1984), Greenhouse effect and sea level rise. Van Nostrand Reinhold, New York

Basher.L.R, Hicks.D.M, McSavenay.M.J, Whitehouse.I.E, (1998), The lower Waimakariri River Floodplain – a geomorphological perspective, Soil Conservation Group Report, Ministry of Works and Development, Christchurch New Zealand, Pp 33

Beach.R, Muhlemann.A.P, Price.D.H.R, Paterson.A, Sharp.J.A, (2001), The role of qualitative methods in production management research, *International Journal of Production Economics*, Vol. 74, Pp 201-212

Bilderback.E, Noble.D, Townsend.D, Begg.J, Jongens.R, Ries.W, Claridge.J, Klahn.A, Mackenzie.H, Smith.A, Hornblow.S, Nicol.R, Cox.S, Langridge.R, Pedley.K, (2010). Surface rupture of the Greendale Fault during the Mw 7.1 Darfield (Canterbury) earthquake, New Zealand: initial findings. *Bulletin of the New Zealand Society for Earthquake Engineering,* Vol. 43, No.4, Pp 236-242

Bird.F.J and Bommer.J.J, (2004) Earthquake losses due to ground failure, *Engineering Geology,* Vol. 47, No. 2, Pp 147-149

Birkmann.J, Buckle.P, Jaeger.J, Pelling.M, Setiadi.N, Garschagen.M, Fernando.N, Kropp.J, (2010), Extreme events and disasters: a window of opportunity for change? Analysis of organizational, intuitional and political changes, formal and informal responses after mega-disasters, *Nat Hazards*, Vol. 55, Pp 637-655, DOI 10.1007/s11069-008-9319-2

Boon.H.J, Cottrell.A, King.D, Stevenson.R.B, Millar.J, (2012), Bronfenbrenner's bioecological theory for modelling community resilience to natural disasters, *Natural Hazards*, Vol. 60, Pp 381-408

Brabhaharan.P, Davey.R, O'Riley.F, Wiles.L, (2005) Earthquake risk assessment study Part 1- review of risk assessment methodologies and development of a draft risk assessment methodology for Christchurch, Opus International Consultants Limited, Report No. U04/108

Bradshaw.M, Wood.L, Williamson.S, (2001), Applying qualitative and quantitative research: a social impact assessment of a fishery, *Applied Geography,* Vol. 21, Pp 69-85

Braun.V and Clarke.V, (2006), Using thematic analysis in psychology, *Qualitative Research in Psychology,* Vol. 3, No. 2, Pp 77-101

Brown.I, Jude.S, Koukoulas.S, Nicholls.R, Dickson.M, Walkden.M, (2006), Dynamic simulation and visualisation of coastal erosion, *Computers, Environment and Urban Systems,* Vol. 30, Pp 840-860

Brown, L. J. and Weeber, J. H, (1992) *Geology of the Christchurch Urban Area*, IGNS Geological Map 1, 1:25,000; Kirk, R. M., 2001: 'Marine processes and coastal landforms', in A. Sturman and R. Spronken-Smith (eds), *The Physical Environment: A New Zealand perspective,* Oxford University Press, Melbourne, Pp 290–306

Buchanan.A, Carradine.D, Beattie.G, Morris.H, (2011), Performance of houses during the Christchurch earthquake of 22 February 2011, *Bulletin of the New Zealand Society for Earthquake Engineering*, Vol. 44, No. 4, Pp 342-357

Burton.I and Kates.R.W, (1964), The perception of natural hazards in resource management, *Natural Resources Journal.* Vol. 3, No. 3, Pp 412-441

Cannon.T, (1994), Vulnerability analysis and the explanation of 'Natural' disasters, In Ann Varley (Eds), *Disasters, Development and Environment*, Pp 13-30, Retrieved from: <http://leeclarke.com/courses/disasters/cannon_vulnerability_analysis.pdf>

Carter, M. and S. Bentley, (1991) Correlations of Soil Properties. Pentech Press. London, England

CERA - Canterbury Earthquake Recovery Authority, (2012), Accessed 20 October 2012, <http://cera.govt.nz/>

CERA – Canterbury Earthquake Authority, (2013), Land damage and geotechnical maps, Digital image, Accessed 18 March 2013, <http://cera.govt.nz/maps>

Chin.A, (2006), Urban transformations of river landscapes in a global context, *Geomorphology*, Vol. 79, Pp 460-487

Collins.D, Kearns.R, (2008), Uninterrupted views: real estate advertising and changing perspectives on coastal property in New Zealand, Environment and Planning A, Vol. 40, Pp 2914-2932

Cousins, J., McVerry, G., (2010), Overview of strong motion data from the Darfield Earthquake. *Bulletin of the New Zealand Society for Earthquake Engineering*, Vol. 43, No. 4, 222-227

Cronin.T.M, (2012), Rapid sea level rise, *Quaternary Science Reviews*, Vol. 56, Pp 11-30

Curbrinovski.M, Bradley.B, Wotherspoon.L, Green.R, Bray.J, Wood.C, Pender.M, Allen.J, Bradshaw.A, Rix.G, Taylor.M, Robinson.K, Henderson.D, Giogini.S, Ma.K, Winkley.A, Zupan.J, O'Rourke.T, DePascale.G, Wells.D, (2011), Geotechnical aspects of the 22 February 2011 Christchurch Earthquake, *Bulletin of the New Zealand Society for Earthquake Engineering*, Vol. 44, No. 4, Pp 205-226

Curbrinovski.M, Henderson. D, Bradley.B, (2012), Liquefaction impacts in residential areas in the 2010-2011 Christchurch earthquakes, Proceedings of the International Symposium on Engineering Lessons learned from the Great East Japan Earthquake, March 1-4, Tokyo, Japan

Cutter.S.L, (1996), Vulnerability to environmental hazards, *Progress in Human Geography,* Vol. 20, No. 4, Pp 529-539

Cutter.S.L, Boruff.B.J, Scott.M.S, (2000), Revealing the vulnerability of people and places: a case study of George Town County, South Carolina, Ann As Am Geogr, Vol. 90, No. 4, Pp 713-737. DOI:10.1111/0004-5608.00219

DiCocco-Bloom.B and Crabtree.B.F, (2006), The qualitative research interview, Medical Education, Vol. 40, Pp 314-321

Dolce.M, Kappos,A, Masi.A, Penelis.G, Vona.M, (2006), Vulnerability assessment and earthquake damage scenarios of the building stock of Potenza (Southern Italy) using Italian and Greek methodology, *Engineering Structures,* Vol. 28, Pp 357-371

Dorwick.D, Cousins.J, Rhoades.D, (2004), Earthquake risk reduction in New Zealand, 13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada, Paper No. 3464

Duxbury.J and Dickinson.S, (2007), Principles for sustainable governance of the coastal zone: in the context of coastal disasters, *Ecological Economics,* Vol. 63, Pp 319-330

Dykes.J, (2000), An approach to virtual environments for visualization using geo-referenced panoramic imagery, *Computers, Environment and Urban Systems,* Vol. 24, Pp 127-152

Elder.D, and McCahon.I, (1990) Near surface groundwater hydrology and excavation dewatering in Christchurch, in Groundwater and Seepage Symposium: Auckland, New Zealand.

Elder.D.M.G, McCahon.I.F. and Yetton.M.D, (1991), *The Earthquake Hazard in Christchurch: A Detailed Evaluation*. Soils & Foundations Ltd, Christchurch. Report funded by the Earthquake Commission.

England.K.V.L, (1994), Getting personal: reflexivity, positionality and feminist research, *The Professional Geographer,* Vol. 46, No. 1, Pp 80-89

Erdik.M, Sesetyan.K, Demircioglu.M.B, Hancilar.U, Zulfikar.C, (2011), Rapid earthquake loss assessment after damaging earthquakes, *Soil Dynamics and Earthquake Engineering,* Vol. 31, Pp 247-266

Forsyth, P.J., Barrell, D.J.A., Jongens, R. 2008. Geology of the Christchurch area. Institute of Geological and Nuclear Sciences 1:250,000 Geological Map 16. 1 sheet +67 p. Lower Hutt, New Zealand. GNS Science.

Fritz.C.E, (1961), Disasters, In: Merton, R.K. Misbet, R.A. (Eds.), Contemporary Social Problems, Harcourt, New York, pp 651-694

Gaber.J, (1993), Reasserting the importance of qualitative methods in planning, *Landscape and Urban Planning*, Vol. 26, Pp 137-148

Gaillard.J.C, (2010), Policy arena, Vulnerability, capacity and resilience: Perspectives for climate and development policy, *Journal of International Development*, Vol. 22, Pp 218-232

Gaillard.J.C, Maceda.A.E, Stasiak.E, Le Berre.I, Espaldon.M.V.O, (2009), Sustainable livelihoods and people's vulnerability in the face of coastal hazards, *Journal of Coastal Conservation*, Vol. 13, Pp 119-129

Gehrels.W.R, Woodworth.P.L, (2013), Why did modern rates of sea level rise start? *Global and Planetary Change*, Vol. 100, Pp 263-277

GNS Science, (2012), 6.3 Magnitude earthquake part of aftershock sequence – 25/2/2011, Digital Image, Accessed 20 March 2013, < http://www.gns.cri.nz/Home/News-and-Events/Media-Releases/earthquake-part-of-aftershock-sequence>

GNS, (2012), 2010 Darfield (Canterbury) earthquake, Digital Image, Accessed 4 September 2012,<http://www.gns.cri.nz/Home/Our-Science/Natural-Hazards/Recent-Events/Canterbury-quake/Darfield-Earthquake>

Goff.J, McFadgen.B, Wells.A, Hicks.M, (2008), Seismic signals in coastal dune systems, *Earth-Science Reviews*, Vol. 89, Pp 73-77

Gornitz.V, (1991), Global coastal hazards from future sea level rise, *Palaeogeography, Palaeoclimotology, Palaeoecology (Global and Planetary Change Section)*, Vol. 89, Elsevier Science Publishers B.V., Amsterdam, Pp 379-398

Guleria.S and Patterson Edward.J.K, (2012), Coastal community resilience: analysis of resilient elements in 3 districts of Tamil Nadu State, India, *Journal of Coastal Conservation*, Vol. 16, Pp 101-110

Hack.R, Alkema.D, Kruse.G.A.M, Leenders.N, Luzi.L, (2007), Influence of earthquakes on the stability of slopes, *Engineering Geology*, Vol. 91, Pp 4-15

Hart.D, (2012), *Christchurch's coastal and river quakes,* 6th Australasian natural hazards management conference 2012, Christchurch, New Zealand

Hannah.J, (2004), An updated analysis of long term sea level change in New Zealand, *Geophysical Research Letters*, Vol. 31, L03307, DOI:10.1029/2003GL019166

Harker.J, (2011), Local authority liability for developments in areas subject to natural hazards, *New Zealand Journal of Environmental Law*, Vol. 15, Pp 277-322

Hewitt.K, (2007), Preventable disasters: Adressing social vulnerability, institutional risk and civil ethics, *Geographisches Rundscahu*: International Edition, Vol. 3/1, Pp 43-52

Hicks.M, Hume.T.M, (1996), Morphology and size of ebb tidal deltas at natural inlets on open seas and pocket bay coasts, North Island, New Zealand, *Journal of Coastal Research*, Vol. 12, No. 1, Pp 47-63

Hill.C.E, Thompson.B.J, Williams.E.N, (1997), A guide to conducting consensual qualitative research, The Counselling Psychologist, Vol. 25, Pp 517-572, DOI: 10.1177/0011000097254001

Hill.H, Wiener.J, Warner.K, (2012), From fatalism to resilience: reducing disaster impacts through systematic investments, *Disasters*, Vol. 36, No. 2, Pp 175-194

Holden.C, Beavan.J, fry.B, Reyners.M, Ristau.J, Dissen.V, Villamor.P, Quigley.M, (2011), Preliminary source model of the Mw 7.1 Darfield earthquake from geological, geodetic and seismic data, Proceedings of the Ninth Pacific Conference on Earthquake Engineering, Building an Earthquake Resilient Society, April 14-16, Auckland, New Zealand, pp 164

Ingham.J.M, Biggs.D.T, Moon.L.M, (2011), How did unreinforced masonry buildings perform in the February 2011 Christchurch earthquake?, *Structural Engineering*, United Kingdom, March 15, 2011

Jacka.M.E and Murahidy.K.M, (2011), Observation and characterisation of land damage due to liquefaction and lateral spreading, Proceedings of the Ninth Pacific Conference on Earthquake Engineering, Building an Earthquake Resilient Society, April 14-16, Auckland, New Zealand, pp 1-8

Javadi.A.A, Rezania.M, Mousavi Nezhad.M, (2006), Evaluation of liquefaction induced lateral displacements using genetic programming, *Computers and Geotechnics*, Vol. 33, Pp 222-233

Kahn, M. (2005). The death toll from natural disasters: The role of income, geography and institutions, *Review of Economics and Statistics*, Vol. 87, No. 2, Pp 271–284

Kam.W.Y and Pampanin.S, (2011), The seismic performance of RC buildings in the 22 February 2011 Christchurch earthquake, *Structural Concrete*, Vol. 12, Is. 4, Pp 223-233

Kaiser.A, Haines.A.J, Benites.R.A, Cochran.E, Chung.A.I, Fry.B, (2011), Effecrs of surface gelology on seismic motion, 4th IASPEI/IAEE International Symposium, August 23-26, University of California, Santa Barabara

Kaiser.A, Holden.C, Beavan.J, Beetham.D, Benites.R, Celentano.A, Collett.D, Cousins.J, Cubrinovski.M, Dellow.G, Denys.P, Fielding.E, Fry.B, Gerstenberger.M, Langridge.R, Massey.C, Motagh.M, Pondard.N, McVerry.G, Ristau.J, Stirling.M, Thomas.J, Uma.S.R & Zhao.J (2012),The Mw 6.2 Christchurch earthquake of February 2011: preliminary report, New *Zealand Journal of Geology and Geophysics*, Vol. 55:1, Pp 67-90

Kappes.M.S, Papathoma-Kohle.M, Keiler.M, (2012), Assessing vulnerability for multi-hazards using an indicator-based methodology, *Applied Geography*, Vol. 32, Pp 577-590

Knigge.L, Cope.M, (2006), Grounded Visualization: integrating the analysis of qualitative and quantitative data through grounded theory and visualisation, *Environment and Planning*, Vol. 38, Pp 2021-2037

Kullenberg.G, (2001), Contributions of marine and coastal area research and observations towards sustainable development of large coastal cities, *Ocean and Coastal Management*, Vol. 44, Pp 283-291

Leckie.D.A, (2003), Modern environments of the Canterbury Plains and adjacent offshore areas, New Zealand – an analogue for ancient conglomeratic depositional systems in nonmarine and coastal zone setting, *Bulletin of Canadian Petroleum Geology*, Vol. 51, No. 4, Pp 389-425

Lewis.J, 1982, Natural Disaster Mitigation: Environmental Approaches in Tonga and Algeria, *The Environmentalist*, Vol. 2, Pp 233-246

Li.H, (2003), Management of coastal mega-cities – A challenge in the 21st century, *Marine Policy*, Vol. 27, Pp 333-337

Lozoya.J.P, Sarda.R, Jimenez.J.A, (2011), A methodological framework for multi-hazards risk assessment in beaches, *Environmental Science and Policy*, Vol. 14, Pp 685-696

Lucas Associates, (2011), 1850 map overlain with post February 2011 earthquake aerial, Digital image, Accessed 18 March 2013,<http://www.lucas-associates.co.nz/christchurch-banks-peninsula/historical-maps/>

Lynos.M, (2009), Building back better: The large scale impact of small-scale approaches to reconstruction, *World Development,* Vol. 37, No. 2, Pp 385-398

Macpherson.J.M, (1979), Response to urbanisation of the Avon-Heathcote Estuary, Christchurch, New Zealand, *Environment Geology*, Vol. 3, Pp 23-27

McEntire.D.A, (2004), Development, disasters and vulnerability: a discussion of divergent theories and the need for their integration, *Disaster Prevention and Management*, Vol. 13, No. 2, Pp 193-198, DOI 10.1108/09653560410541786

McFadgen.B.G and Goff.J.R, (2005), An earth systems approach to understanding the tectonic and cultural landscape of linked marine embayments: Avon-Heathcote Estuary (Ihutai) and Lake Ellesmere (Waihora), New Zealand, *Journal of Quaternary Science*, Vol. 20, Pp 227-237.

McMurtrie.S, (2011), Christchurch February earthquake: Effect on invertebrates of lower rivers, EOS Ecology Report NO: 11013-CIV01-01

Measures.R, Hicks.M, Shankar. U, Bind.J, Arnold.J, Zeldis.J, (2011), Mapping earthquake induced topographical change and liquefaction in the Avon-Heathcote Estuary, Environment Canterbury Report No: U11/13

Menoni.S, Molinari.D, Parker.D, Ballio.F, Tapsell.S, (2012), Assessing multifaceted vulnerability and resilience in order to design risk-mitigation strategies, *Natural Hazards*, DOI 10.1007/s11069-012-0134-4

Milashuk.S and Crane.W, (2012), Pipeline damage caused by transient ground deformation: Case study of the 2010 Darfield and 2011 Christchurch earthquakes, *Soil Dynamics and Earthquake Engineering*, Vol. 41, Pp 84-88

Ministry for the Environment (2008). Coastal Hazards and Climate Change. A Guidance Manual for Local Government in New Zealand. 2nd edition. Revised by Ramsay, D, and Bell, R. (NIWA). Prepared for Ministry for the Environment. Pp 127

Ministry for the Environment (2008). *Climate Change Effects and Impacts Assessment: A Guidance Manual for Local Government in New Zealand.* 2nd Edition. Mullan. B, Wratt. D, Dean. S, Hollis. M, Allan. S, Williams. T, Kenny. G and MfE. Ministry for the Environment, Wellington, Pp 143-149

Ministry for the Environment, (2013), Part one: The changing climate, Digital image, Accessed 18 March 2013, < http://www.mfe.govt.nz/publications/climate/preparing-for-coastal-change-guide-for-local-govt/html/page1.html>

New Zealand Centre for Advanced Engineering, (1997), Risk and Realities, A Multi-disciplinary Approach to the Vulnerability of Lifelines to Natural Hazards. Report of the Christchurch Engineering Lifelines Group.

New Zealand Coastal Policy Statement, (2010), New Zealand Department of Conservation, Wellington, New Zealand

Nicholls.R.J, Mimura.N, (1998), Regional issues raised by sea level rise and their policy implications, *Climate Research,* Vol. 11, Pp 5-18

Nuno Martine.V, Sousa e Silva.D, Cabral.P, (2012) Social vulnerability assessment to seismic risk using multicriteria analysis: the case study of Vila Franca do Campo (Sao Miguel Island, Azores, Portugal), *Natural Hazards*, DOI 10.1007/s11069-012-0084-x

Obermeier.S, (1996), Use of liquefaction induced features of paleoseismic analysis – An overview of how seismic liquefaction features can be distinguished from other features and how their regional distribution and properties of source sediment can be used to infer location and strength of Holocene paleo-earthquakes, Engineering Geology, Vol. 44, Is 1-4, Pp 1-76

O'Keefe .P, Westgate. K, Wisner.B, (1976), Taking the naturalness out of natural disasters, *Nature,* Vol. 260, Pp 566-567

O'Neill.S.J, Osborn.T.J, Hulme.M, Lorenzoni.I, Watkinson.A.R, (2008), Using expert knowledge to assess uncertainties in future polar bear populations under climate change, Journal of applied Ecology, Vol. 45, Pp 1649-1659, doi: 10.1111/j.1365-2664.2008.01552.x

Page.T, Heathwaite.A.L, Thompson.LJ, Pope.L, Willows.R, (2012), Eliciting fuzzy distributions from experts for ranking conceptual risk model components, *Environmetal Modelling and Software,* Vol. 36, Pp 19-34

Parker.M and Steenkamp.D, (2012), The economic impact of the Canterbury earthquakes, *Reserve Bank of New Zealand: Bulletin*, Vol. 75, No. 3, Pp 13-25

Pate.E.J, Kron.W, Borm.C, (1994), The international decade for natural disaster reduction (IDNDR): A challenge to science, *Soil Dynamics and Earthquake Engineering,* Vol. 13, Pp 45-48

Pavlovskaya.M, (2006), Theorizing with GIS: a tool for critical geographies? *Environment and Planning,* Vol. 38, Pp 2003-2020

Peters-Guarin.G, McCall.M.K, van Westen.C, (2012), Coping strategies and risk manageability: using participatory geographical information systems to represent local knowledge, *Disasters,* Vol. 36(I), Pp 1-27, doi:10.1111/j.1467-7717.2011.01247.x

Pethic.J, (2001), Coastal management and sea level rise, *Catena*, Vol. 42, Pp 307-322

Pettinga.J.R, Yetton.M.D, Dissen.R.J.V, Downes.G, (2001), Earthquake source identification and characterisation for the Canterbury region, South Island, *New Zealand*, *Bulletin of the New Zealand Society for Earthquake Engineering*, Vol. 34, No. 4, Pp 282-316

Pettit.C.J, Raymond.C.M, Bryan.B.A, Lewis.H, (2011), Identifying strengths and weaknesses of landscape visualisation for effective communication of future alternatives, *Landscape and Urban Planning,* Vol. 100, Pp 231-241

Polermo.A, Wotherspoon.L, Hogan.L, Le Heux.M, Camnasio.E, (2011) Seismic performance of concrete bridges during the Canterbury earthquakes, *Structural Concrete*, Vol. 13, No. 1, Pp 14-26

Prakash.S and Sandoval.J.A, (1992), Liquefaction of low plasticity silts, *Soil Dynamics and Earthquake Engineering,* Vol. 11, Pp 373-379

Redzone tours, (2012), Liquefaction – Avon/ Heathcote Estuary, Digital Image, Accessed 18 March 2013, <http://redzonetours.co.nz/red-zone-gallery/>

Rose.A, (2004), Defining and measuring economic resilience to disasters, *Disaster Prevention and Management*, Vol. 13, No. 4, Pp 307-314, DOI 10.1108/09653560410556528

Rose.G, (1997), Situating Knowledges: positionality, reflexivity and other tactics, *Progress in Human Geography*, Vol. 21, No. 3, Pp 305-320

Rosier.J and Hastie.W, (1996), New Zealand coastal planning: an issue based approach, *Ocean and Coastal Management*, Vol. 33, No. 1-3, Pp 147-165

Ross.A.J, Davies.J.R, Plunkett.M, (2005), Reliable qualitative data for safety and risk management, *Process Safety and Environmental Protection*, Vol. 83(B2), Pp 117-121

Sales Jr.R.F.M, (2009), Vulnerability and adaptation of coastal communities to climate variability and sea-level rise: Their implications for coastal management in Cavite City, Philippines, *Ocean and Coastal Management*, Vol. 52, Pp 395-404

Samarasinghe.S, Strickert.G, (2012), Mixed-method integration and advances in fuzzy cognitive maps for computational policy simulations or natural hazard mitigation, *Environmental Modelling and Software xxx (*Article in Press), Pp 1-13, http://dx.doi.org/10.1016/j.envsoft.2012.06.008

Sapountzaki.K, (2012) Vulnerability management by means of resilience, *Natural Hazards*, Vol. 60, Pp 1267-1285

Saunders. W.S.A., Beban, J.S., (2012) Putting R(isk) in the RMA: Technical Advisory Group recommendations on the Resource Management Act 1991 and implications for natural hazards planning, *GNS Science Miscellaneous Series,* Vol. 48, Pp 57.

Saunders.W.S.A and Berryman. K.R, (2012), Just add water: when should liquefaction be considered in land use planning, *GNS Science Miscellaneous Series*, Vol. 47, Pp 15

Seneviratne.K, Baldry.D, Pathirage.C, (2010), Disaster knowledge factors in managing disasters successfully, *International Journal of Strategic Property Management*, Vol. 14, No. 4, Pp 376-390

Sewell. R.J, Weaver.S.D, Reay.M.B. (1992) Geology of Banks Peninsula. Scale 1:100 000. *Institute of Geological and Nuclear Sciences geological map 3.* Lower Hutt, Institute of Geological and Nuclear Sciences.

Sheppard.S.R.J, (2005), Landscape visualisation and climate change: the potential for influencing perceptions and behaviour, *Environmental Science and Policy*, Vol. 8, Pp 637-654

Shomoto.Y, Zhang.J.M, Tokimatsu.K, (1998), New charts for predicting large residual post-liquefaction ground deformation, *Soil Dynamics and Earthquake Engineering,* Vol. 17, Pp 427-438

Shulmeister.J and Kirk.R.M, (1993), EVol.ution of a mixed sand and gravel barrier system in North Canterbury, New Zealand, during Holocene sea level rise and still-stand, *Sedimentary Geology*, Vol. 87, Pp 215-235

Sinclair.M, (2008), Local Civil Defence Emergency Management Arrangements, Report published by The Christchurch City Council.

Smith. S, (2000) ``Qualitative methods'', in The Dictionary of Human Geography, Eds R J Johnston, D Gregory, G Pratt, M Watts (Blackwell, Oxford), Pp 660 -662

Sovacool.B.K, D’Agostino.A.L, Meenawat.H, Rawlani.A, (2012), Expert views of climate change adaptation in least developed Asia, *Journal of Environmental Management,* Vol. 97, Pp 78-88

Stenchion.P, (1997), Development and disaster management, *Australian Journal of Emergency Management,* Vol. 12, Is 3, Pp 40-44, Retrieved from: http://search.informit.com.au/documentSummary;dn=397086657696665;res=IELHSS

Stevenson.J.R, Kachali.H, Whitman.Z, Seville.E, Vargo.J, Wilson.T, (2011), Preliminary observations of the impacts of 22 February Christchurch earthquake on organisations and the economy: A report from the field (22 February-22 March 2011), *Bulletin of the New Zealand Society for Earthquake Engineering*, Vol. XX, No Y, Pp 1-12

Stirling, M., Gerstenberger, M., Litchfield, N., McVerry, G., Smith, W., Pettinga, J., Barnes, P. 2008. “Seismic hazard of the Canterbury region, New Zealand: new earthquake source model and methodology”. *Bulletin of the New Zealand Society for Earthquake Engineering,* Vol. 41, Pp 51-67.

Stramondo.S, Kyriakopoulos.C, Bignami.C, Chini.M, Melini.D, Moro.M, Picchiani.M, Saroli.M, Boschi.E, (2011), Did the September 2010 (Darfield) earthquake trigger the 2011 (Christchurch) event, *Scientific Reports*, Vol. 1:98, DOI:10.1038/srep00098

Suggate.R.P, (1963), The fan surfaces of the central Canterbury Plain, *New Zealand Journal of Geology and Geophysics*, Vol. 6:2, Pp 281-287

Suggate, R.P.(1958) Late Quaternary deposits of the Christchurch Metropolitan area. *New Zealand Journal of Geology and Geophysics*, Vol. 1, Pp 281-287.

Tran.L.T, O'Neill.R.V, Smith.E.R, (2010), Spatial patterns of environmental vulnerability in the Mid-Atlanitc region, USA, Applied Geography, Vol. 30, Iss 2, Pp 191-202

Valsamis.A.I, Bouckovalas.G.D, Papadimitriou.A.G, (2010), Parametric investigation of lateral spreading of gentle sloping liquefied ground, *Soil Dynamics and Earthquake Engineering,* Vol. 30, Pp 490-508

Vogel.C, Moser.S.C, Kasperson.R.E, Dabelko.G.D, (2007), Linking vulnerability, adaptation, and resilience science to practice: pathways, players and partnerships, *Global Environmental Change,* Vol. 17, Pp 349-364

Warrick.R.A, Oerlemans .J, Woodworth.P.L, Meier.M.F, le Provost.C, (1996), Changes in sea level. In: Houghton JT, Meira Filho LG, Callander BA (eds) Climate change 1995: the science of climate change. Cambridge University Press, Cambridge, Pp 359–405

Watts.R, (2005), A strategy for the protection and restoration of waterways and wetlands in Christchurch, Greening the City, Section Four: Focus on Canterbury, Pp 168-179, ISBN 0-959-77566-8

Weiran.Y, Zuoxun.Z, Dewei.L, Jishan.X, Jie.W, Wenxing.L, (2009), Three-level tectonic model for intraplate earthquakes, *Earth Science Frontiers*, Vol. 16 , Is. 1, Pp 206-217

Westgate.K.N and O'Keefe.P, (1976), Some definitions of disasters, Disaster Research Unit Occasional Paper No.4, Department of Geography, University of Bradford

White.G.F, Kates.W.R, Burton.I, (2001), Knowing better and losing even more: the use of knowledge in hazards management, *Environmental Hazards,* Vol. 3, Pp 81-92

White.P.A, (2009), Avon River springs catchment, Christchurch City, New Zealand, *Australian Journal of Earth Sciences*: *An International Geoscience Journal of the Geological Society of Australia*, Vol. 56, No. 1, Pp 61-70

Wilson.D.D, (1976), Hydrogeology of metropolitan Christchurch, *Journal of Hydrology (N.Z.)*, Vol. 15, No. 2, Pp 101-120

Wong.I, Bouabid.J, Graf.W, Huyck.C, Porush.A, Silva.W, Siegel.T, Bureau.G, Eguchi.R, KnightJ, (2005), Potential losses in a repeat of the 1886 Charleston, South Carolina earthquake, *Earthquake Spectra*, Vol. 21, No. 4, Pp 1157-7784

Wood.N.J and Good.J.W, (2004) Vulnerability of Port and Harbor Communities to Earthquake and Tsunami Hazards: The Use of GIS in Community Hazard Planning, *Coastal Management*, Vol. 32:3, Pp 243-269

Wood.P, Robins.P, Hare.J, (2010), Preliminary observations of the 2010 Darfield (Canterbury) earthquakes: An introduction, *Bulletin of the new Zealand Society for Earthquake Engineering*, Vol. 43, No. 4, Pp 1-4

Woodroffe.C.D, Murray-Wallace.C.V, (2012), Sea level rise and coastal change: The past as a guide to the future, *Quaternary Science reviews*, Vol. 54, Pp 4-11

Wotherspoon.L.M, Pender.M.J, Orense.R.P, (2012), Relationship between observed liquefaction at Kaiapoi following the 2010 Darfield earthquake and former channels of the Waimakiriri River, *Engineering Geology*, Vol. 125, Pp 45-55

Young.D, 'Rivers', Te Ara - the Encyclopedia of New Zealand, updated 16-Mar-09, URL: http://www.TeAra.govt.nz/en/rivers

Yucemen.M.S, Ozcebe.G, Pay.A.C, (2004), Prediction of potential damage due to severe earthquakes, *Structural Safety*, Vol. 26, Pp 349-466

Yuen Kam.W and Pampanin.S, (2011), The seismic performance of RC buildings in the 22 February 2011 Christchurch earthquake, *Structural Concrete*, Vol. 12, No. 4, Pp 223-233

Zeldis.J, Skilton.J, South.P, Schiel.D, (2011), Effects of the Canterbury earthquakes on Avon-Heathcote Estuary/Ihutai ecology, Environment Canterbury report No: U11/14

APPENDIX

Appendix 1: Human Ethics Approval Letter

Secretary Lynda Griffioen

Email: human-ethics@canterbury.ac.nz

Ref: HEC 2012/92

27 July 2012

Emma Kelland and Deirdre Hart Department of Geography UNIVERSITY OF CANTERBURY

Dear Emma and Deirdre

The Human Ethics Committee advises that your research proposal "Vulnerability to seismic hazards in coastal and riverside communities: lessons from the Canterbury earthquake sequence" has been considered and approved.

Please note that this approval is subject to the incorporation of the amendments you have provided in your email of 24 July 2012.

Best wishes

Yours sincerely

Michael Grimshaw

Chair

University of Canterbury Human Ethics Committee

University of Canterbury Private Bag 4800, Christchurch 8140, New Zealand. **www.canterbury.ac.nz**

Appendix 2: Interview Questions

Could you please tell us your name and professional title and a bit about your background and what you role is at present?

Has your role changed since the earthquakes?

In your experience, which areas of Christchurch appeared to have suffered the most significant effects as a result of the 2010 and 2011 earthquakes?

What are the effects that you observed or know about in these areas?

Have you been involved with any assessments of these effects or have you had any thoughts about why these effects have been so significant?

What do you believe caused these areas to be more vulnerable to these effects?

As a result of the earthquakes have you noticed that there is an association between negative effects and coastal and riverside environments?

Do you believe that coastal and riverside environments are more vulnerable to the effects of earthquakes and if so why do you think this is?

Do you think that coastal and river side environments had been recognised as areas vulnerable to earthquake effects prior to the earthquake sequence?

Do you believe that the vulnerability of coastal and river side environments to earthquake have been considered in the rebuild plans of Christchurch, and could you explain why or why not?

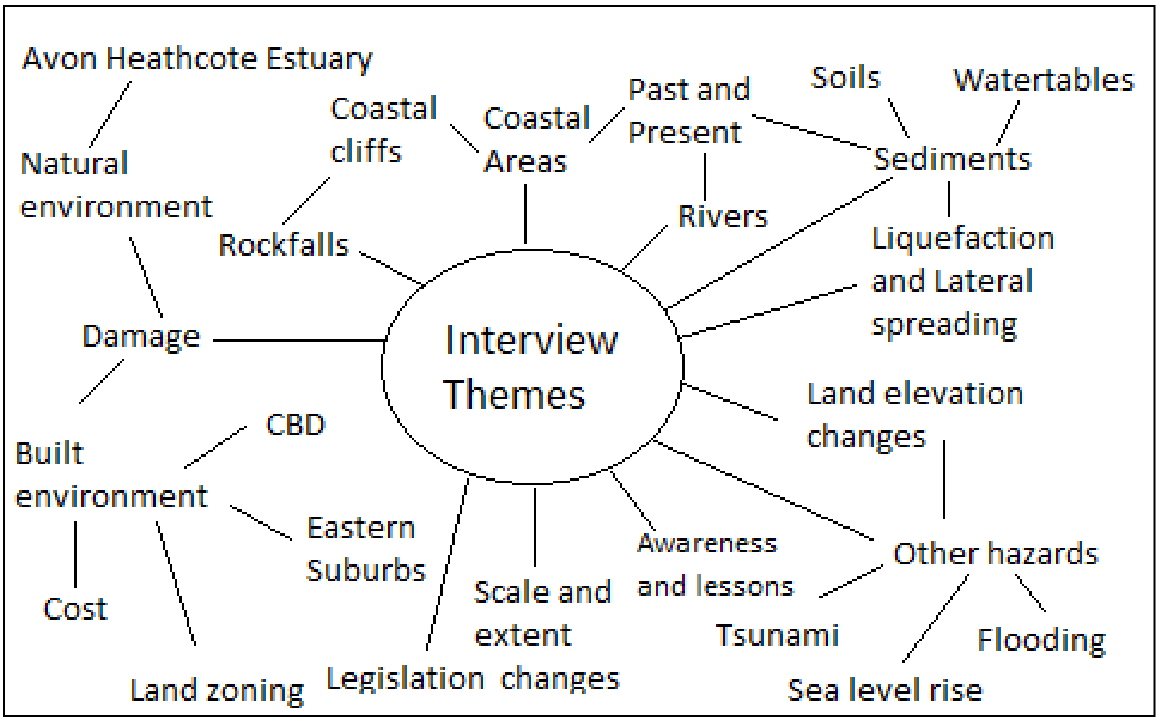
What do you believe should be done in terms of rebuilding along coastal and riverside environments or how do you think coastal and river side areas can be made more resilient to hazards?

Do you think that the effects of the earthquakes will have an influence on future coastal and river hazards and if so on what hazards and how?

Do you think it would be important to include earthquakes in coastal hazard plans or the coastal policy statement in a way that Tsunami have been is included?

Is there any other information that you have might about the relationship between earthquake hazards and coastal and river environment or you what you think I should be focussing more on?

Appendix 3: Thematic Map of Interview Themes



Appendix 4: Additional changes to section 6 and 7 of the RMA

The proposed changes to sections 6 and 7 as recommended by the Technical Advisory Group would be supported by the following definitions

Natural hazards:

A provision requiring decision-makers to recognise and provide for issues around natural hazard risks should be incorporated in s.6 of the RMA – the wording of the provision to be, "managing the significant risks associated with natural hazards:"

Retain the RMA definition of natural hazards. Further work should be undertaken on alignment of the definition across all relevant legislation, in particular to take account of the differing "return periods" for natural hazards.

Amend provisions specifying matters to be considered in preparing RPS and plans to specifically refer to CDEM Group management plans as a matter which must be considered.

Regional councils should have the lead function of managing all the effects of natural hazards. Territorial authorities are to retain their current function in regard to natural hazards.

There should be one combined regional and district natural hazards plan.

This plan should be required to be operative within three years of enactment of the empowering legislation.

Require local authorities to make information about natural hazards available to all other local authorities within their region. This requirement should be drafted to expressly override any constraints arising from other legislation on information sharing, including the Privacy Act 1993 and the Local Government Official Information and Meetings Act 1987.

Section 106 be amended to expressly include liquefaction and lateral spreading, along with any other consequences of the events included in the definition of "natural hazard" in s.2.

Section 106 be amended to reflect the risk associated with any natural hazard, rather than the likelihood of the event.

Section 106 be amended so that the consent authority must refuse consent if there will be a significant increase in the risk associated with any natural hazard.

That the potential to extend the scope of s.106 to include land use consents issued by regional councils be investigated.

That the Government promulgate a NPS or NES on the management of natural hazards.